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The Needed Minimum Submergence Depth When a Submarine Runs into Typhoon

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Abstract In this paper, the influence depths of all levels of wind power produced waves are reckoned according to the measured swaying degree when a submarine meets with a force 11 strong tropical storm and has to submerge; Then the minimum submergence depth is given when a submarine is faced with weather systems with force ≥ 6 wind and the swaying degree of less than 12 degree is assured as reference for a submarine working and sailing in big strong winds and waves.

Keywords minimum submergence depth, submarine, swaying degree

1 Introduction

When a sailing submarine meets with a storm^[1], it can take the measure of submerging to avoid wind wave besides quickly sailing off the storm area like the surface naval fleet. However, the effect is very serious when it meets with a longer-waved swell produced by strong weather systems such as cold wave, strong cyclone, and typhoon and so on. Under such condition, the submarine needs to submerge deeper to diminish the influence. It is very important to master the degree of submergence. Otherwise, if it is too deep, it is difficult to steer the submarine; if too shallow, the submarine is still influenced by wave. The reference data of the appropriate submergence depth needed are given in this paper for different weather systems. And the submergence depths needed when a submarine encounters with different-scaled tropical cyclones (typhoon) are separately collected as reference for sailing of submarines.

2 Brief introduction to a submarine raided by a force 11 strong tropical storm

In the mid-1970s, a submarine suffered from a force 11 strong tropical cyclone. At that moment, the wave was 10 meters high, and the wave of the great swell was 100 to 200 miles long, which made the swaying of the submarine sailing on the water surface reach more than 50 degrees, and the log fail to work. Under such condition, the coxswain had to issue an order of submergence. When the submergence depth reached 60 meters, the swaying fell to 18 degree; and when the depth reached 70 meters, the swaying fell to 12 degree. The submarine had sailed for 12 sea miles under water and managed to avoid the typhoon for over 30 hours. The communication to the outside was cut off, and the power supply for cooking and air conditioning was very difficult. In this instance, the submarine avoided great loss because of the correct deep submergence.

3 The calculation of the depth affected by the waves produced by all levels of wind force

Let us define the swaying degree of a submarine as Y_n and the depth as h , and the empirical equation is as follows:

$$Y_n = A \times h^2 + B \times h + C_n \quad (1)$$

where A and B are constants, and C_n is the swaying degree produced by force- n wind when the submarine is on the water surface.

Tab. 1 The measured swaying degree when the submarine has to submerge

Depth (miles)	Swaying degree
0	50
60	18
70	12

According to the swaying degree of the submerging submarine given in Table 1, Formula (2) is given as follows:

$$Y_n = -\frac{1}{1050} \times h^2 - \frac{10}{21} \times h + 50 \quad (2)$$

According to Table 2, the wave height caused by a force 11 wind is 11.5 meters, then the ratio of wave height and swaying degree is:

$$K = \frac{h11}{y11} = \frac{11.5}{50} = 0.23 (m/d) \quad (m \text{ is meter and } d \text{ is degree}) \quad (3)$$

On the basis of the ratio and the wind scale table, C_n is got. Then A , B in the formula (1) is replaced by ' $\frac{1}{1050}$ ', ' $\frac{10}{21}$ ' respectively, and C_n is replaced by the value given in Table 2 h_n , when Y_n equals zero, is got, which is the influence depth. When the wind power is less than force 5, the submarine need not submerge; and when the wind power is greater than force 6, the needed submergence depth is given in Table 2.

4 The swaying degree of submarine in face of typhoon waves

Tropical cyclone is a warm low pressure occurring in the tropical ocean, which is called typhoon by our custom. The destructive power of tropical cyclone is very strong, which seriously threatens navigation safety. Therefore, it is very necessary to take active measures to guard against, resist and avoid typhoon so as to diminish and avoid the damage.

The scale standard of tropical cyclone used in China before December 31, 1989 is: force 6 to 7 wind power is called tropical low pressure^[2]; force 8 to 11 wind power is called typhoon; force 12 or greater wind power is called strong typhoon. The worldwide used name and scale standard of tropical cyclone have been introduced since Jan. 1, 1990.

According to the wind power around the center of every level of tropical cyclone, the

corresponding influence depth can be looked up in Table 2 and the minimum submergence depth needed when the submarine keeps the swaying degree less than 12 degrees can be looked up in Table 3. Due to less observing samples, the computed result is coarse. However, the data are of important reference value to the study of wave influence depth and the sailing under harsh conditions.

Tab. 2 Wind scale

Wind scale	Wind name	Wave height (mile)		Sign of sea surface	Corresponding wind		Wind pressure (kg/m ²)	Water surface swaying degree C _n (degree)	Wave influence depth (m)	The minimum submergence depth when n=12 degrees (m)
		normal	highest		(m/s)	(sea mile/h)				
0	Without wind	calm	calm	Sea surface is quiet	0-0.2	<1	0-0.004	0	0	0
1	Soft wind	0.1	0.1	Little ripple	0.3~1.5	1~3	0.009~0.225	0.4	0.8	0
2	Light wind	0.2	0.3	Light wave like scales without spray	1.6~3.3	4~6	0.256~1.089	0.9	1.9	0
3	Breeze	0.6	1.0	Little wave crest with spray sometimes	3.4~5.4	7~10	1.156~2.916	2.6	5.4	0
4	Zephyr	1.0	1.5	Wave is bigger and spray of wave crest is obvious	5.5~7.9	11~16	3.025~6.241	4.3	8.9	0
5	Clear wind	2.0	2.5	Wave is bigger and white water occupies big area	8.0~10.7	17~21	6.4~11.449	8.7	17.6	0
6	Strong wind	3.0	4.0	White water with foam	10.8~13.8	22~27	11.664~19.044	13	26	2.1
7	High wind	4.0	5.5	Foam flies and falls in trough	13.9~17.1	28~33	19.321~29.241	17.4	34.2	11.1
8	Gale	5.5	7.5	Foam fills sea surface and flies in the lower air	17.2~20.7	34~40	29.58~42.85	23.9	46	23.9
9	Violent wind	7.0	10.0	Wave is surging, the lower air is filled with foams, and the visibility is down	20.8~24.4	41~47	43.26~59.54	30.4	57.3	36
10	Squall	9.0	12.5	The lower air is filled with foams, the sailing is difficult and dangerous	24.5~28.4	48~55	60.03~80.66	39.1	71.8	51.6
11	Storm wind	11.5	16.0	The wave is great, and the ship is sinking in the trough	28.5~32.6	56~63	81.23~106.28	50	89.1	70
12	Hurricane	14.0	-	The surf is dashing to sky	>32.6	>63	>106.28	60.9	105.6	87.4

Tab. 3 Names and scale standards of tropical cyclones

Maximum wind power around the center	Name of tropical cyclone	Code name	Influence depth (m)	The minimum submerging depth (m)
6	tropical depression	TD	34.2	11.1
7				
8	tropical storm	TS	57.3	36
9				
10	severe tropical storm	STS	89.1	70
11				
12	typhoon	Ty	105.6	87.4

Note: The internationally used wind scale is the average wind speed per 10 minutes, and because the condition of wind measurement in China is limited, two-minute average wind speed is still in use and expressed by the Beaufort wind scale.

Acknowledgements

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Space-Time Characteristic Analysis of Wind Field over the South Indian Ocean

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Abstract According to the ship observation data over the South Indian Ocean during 1950 — 1995, taking $1^{\circ} \times 1^{\circ}$ and $5^{\circ} \times 5^{\circ}$ grid, the characteristics and variation rule of wind are analyzed. Through analyzing the chart of isopleths of the monthly elements, the conclusion that the seasonal variation of the wind field over the South Indian Ocean is less remarkable than that in the oceans of the Northern Hemisphere is got. The seasonal variation of the wind field is also obvious in this region, but the seasonal difference is little. The wind in winter is stronger than in summer, correspondingly, the average wind speed is higher, and the frequencies of gale of forces ≥ 6 and 8 are also higher. The north of 10° S is a monsoon area; Southeast wind prevails all over the year in the rest of the trade wind area; Westerly wind dominates in the south of 40° S. This paper provides specific data of wind field and variation for ship ocean transportation, ocean-going visits and scientific experiment.

Keywords South Indian Ocean, Pressure field, Wind field

1 Introduction

The South Indian Ocean is the only way which must be passed in marine traffic among Africa, Asia and Oceania. With the development of the international traffic, it becomes more and more frequent to navigate over the South Indian Ocean. More and more hydrometeorological safeguards especially the safeguards of important cruise lines are required. However, data for the region in China is absent except the *Indian Ocean Climate Atlas* (1973)^[1] which has short fixed number of years and takes $5^{\circ} \times 5^{\circ}$ grid (taking $10^{\circ} \times 10^{\circ}$ grid in the south of 40° S), so the existing ship observation data not only are important in ocean safeguards, but also help us to know more characteristics of wind field in this area. Based on the ship observation data during 1950 — 1995 in the South Indian Ocean, with data from several thousands to 6 thousand stations in every $5^{\circ} \times 5^{\circ}$ grid, through analyzing the monthly directions of prevailing wind (taking $5^{\circ} \times 5^{\circ}$ grid), average wind speed, mean pressure and frequencies of gale of forces ≥ 6 and 8 taking $1^{\circ} \times 1^{\circ}$ grid (taking $5^{\circ} \times 5^{\circ}$ grid in the south of 40° S), the essential features and patterns of wind in the South Indian Ocean have been obtained.

2 Pressure on the sea surface

The South Indian Ocean borders Africa in the west, Asia, Timor Sea and Oceania in the east, the equator in the north, and Antarctica in the south. Its western border is 20° E to the south of Africa. Its

eastern border is $146^{\circ} 49' 25''$ E to the south of Oceania. Because data are absent, the north of 60° S is discussed in this paper.

In this region, the pressure field on the sea surface is dominated by subtropical high, westerlies, the Indian monsoon and Antarctic low *etc.*^[2]. The seasonal variation of the wind field is less remarkable than that in the oceans of the Northern Hemisphere^[3-5, 7], but it is also obvious. The seasonal variation of the wind field in the region is the biggest in all the oceans of the Southern Hemisphere^[6]. Its evident characteristic is that the mean pressure on the sea level is controlled by subtropical high centered at 35° S, 75° E all over the year. The center moves away 5 latitude degrees between WNW and ESE all over the year. It moves to the southernmost in the summer and to the northernmost in the winter. The tropical convergence zone trends northeast-southwestward, its center being near 10° S in January and near the equator in July. The circulation of the Indian Ocean is affected most by the surrounding continent among the circulations of global oceans. The north of 10° S is controlled by the Indian monsoon. To the south of 40° S, the baric gradient in the sea area is as great as 2 hPa per latitude degree.

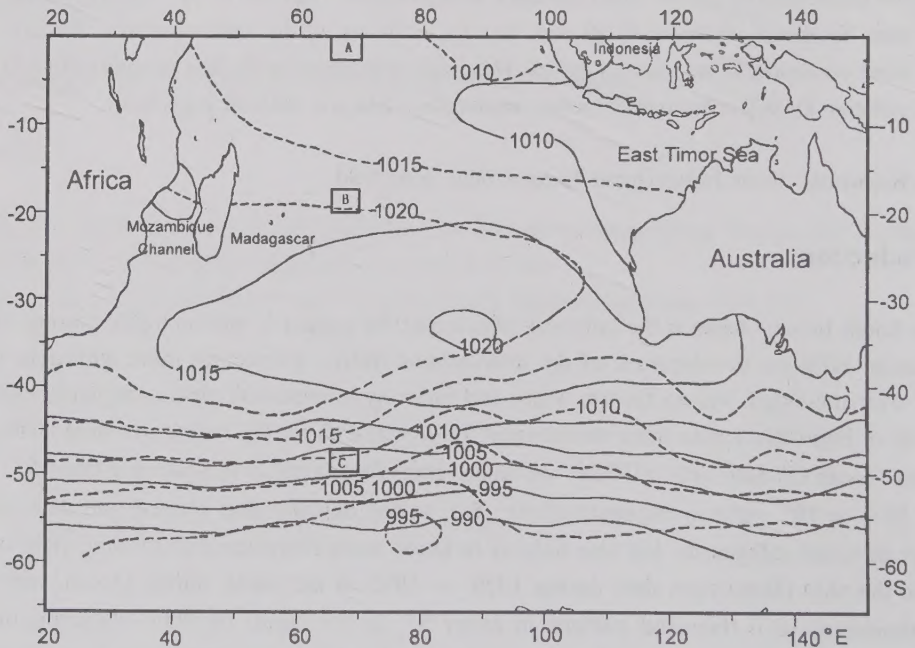


Fig. 1 Monthly average pressure on the sea surface distribution in January and July over the South Indian Ocean

(— Average sea level pressure isopleths in January, --- Average sea level pressure isopleths in July)

2.1 Winter period

June ~ September is the winter period. In this period, the subtropical high reaches the strongest and the northernmost. Its center is near 30° S, 65° E. Its mean pressure ≥ 1025 hPa. The mean pressure ≥ 1020 hPa in most of the sea area between 20° and 40° S. It drops to 1010 hPa slowly from the center

of subtropical high to the equator northward, and the baric gradient is the greatest all over the year; also reduces to 1 000 hPa southward rapidly near 60° S, and in July even 995 hPa in a small region near 60° S, 80° E.

2.2 Alternation season

April ~ May is the alternation season from summer to winter. October ~ November is the alternation period from winter to summer. In this season, the pressure field on the sea surface is similar to that in winter, but the center of subtropical high reaches near 35° S, 80° E southward and the mean pressure reduces appreciably. The mean pressure $\geq 1\,020$ hPa, and the 1 015 hPa isobar appears no longer. The variation of mean pressure from the center of subtropical high to the equator northward is basically consistent with that in winter, but the mean pressure reduces at the center, so the baric gradient decreases; also the mean pressure reduces to 990 hPa near 60° S southward, and the range of 995 hPa isobar is more extendable than that in winter evidently.

2.3 Summer period

December ~ March is the summer period. The subtropical high is the weakest and reaches near 35° S, 90° E southward. Its mean pressure is 1 015 hPa, that is, the lowest all over the year. The variation of the mean pressure from the center of subtropical high to the equator is not great, and the baric gradient is the smallest all the year round; In the sea area between 40° and 60° S, the mean pressure reduces rapidly from 1 015 hPa to below 990 hPa. The South Indian Ocean is crossed by the 995 hPa isobar near 55° S from east to west and the baric gradients are all 2hPa in the sea area between 45° S and 55° S.

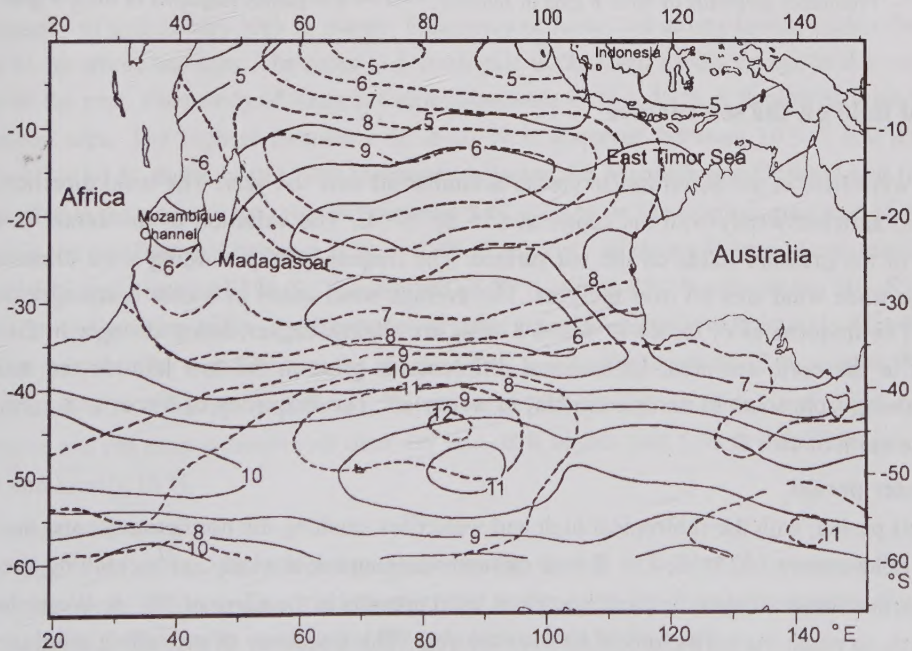


Fig. 2 Monthly average wind speed distribution in January and July over the South Indian Ocean
(— Average wind speed isopleths in January, --- Average wind speed isopleths in July)

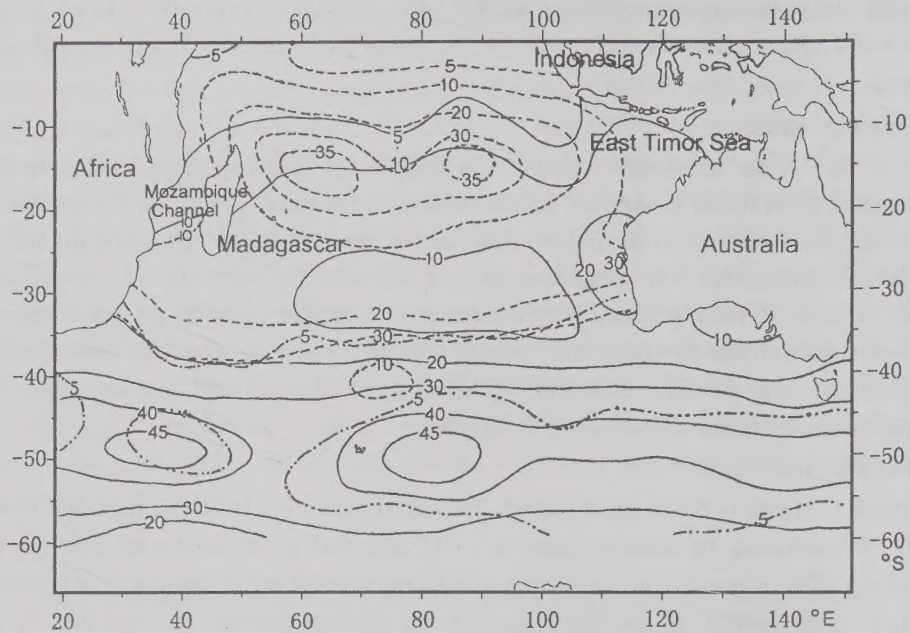


Fig. 3 Frequencies distribution of gales of forces ≥ 6 and 8 in January and July over the South Indian Ocean

(— Frequency isopleths of force 6 gale in January, --- Frequency isopleths of force 6 gale in July)
 (— · — · — Frequency isopleths of force 8 gale in January, — · — · — Frequency isopleths of force 8 gale in July)

3 Wind field on the sea surface

The wind field in the South Indian Ocean is similar all over the year. The wind direction basically goes round anticlockwisely with the center at 35° S, 75° E. The variation of the center is consistent with that of the pressure fields on the sea surface. The frequency of prevailing wind direction is very high in the trade wind area all over the year. The average wind speed in winter is stronger than that in summer. The frequencies of forces ≥ 6 and 8 gales are slightly higher, being stronger in the south sea area than in the north sea area. Its seasonal difference is great in the low latitude sea area and the seasonal swing from south to north is evident to westerlies. The frequency of forces ≥ 8 gales is almost zero to the north of 40° S.

3.1 Winter period

In this period, with the subtropical high and westerlies reaching the northernmost and the strongest, the wind field centers at 35° S, 75° E and circumrotates anticlockwisely, also reaching the strongest and the northernmost all over the year. Southeast wind prevails in the north of 30° S. Westerlies extends to the north, to reach the northernmost all over the year. The frequency of prevailing wind is very high. The range of gale is the most extensive and moves to the northernmost all over the year. The frequency of gale is the highest all over the year and its intensity in the south sea area is higher than that in the north sea area.

3.1.1 Direction of prevailing wind

In winter, the wind field is in the northernmost all over the year, while the subtropical high and westerlies move northward. The westerly wind prevails to the south of 35° S. Westerlies is slightly raised northward from the east of Africa to east, even extends to 30° S to the east of 90° E in July with the frequencies of wind direction between $45\% \sim 72\%$. The wind direction is in disorder between $30^{\circ} \sim 35^{\circ}$ S, but the northeast wind dominates the small western region. Southeast wind prevails between $0^{\circ} \sim 30^{\circ}$ S. Trade wind is most extensive and the strongest all over the year. Frequency of wind direction is as high as $80\% \sim 98\%$. While the subtropical high moves to the north, the strong trade wind area between $5^{\circ} \sim 20^{\circ}$ S reaches the northernmost and the westernmost all over the year. Because the wind over the Mozambique Channel is blocked by Madagascar, the frequency of wind direction is as low as $70\% \sim 80\%$. South wind dominates the tropical area west of the sea area under the influence of prevailing wind and landform. Frequency of wind direction is $85\% \sim 96\%$.

3.1.2 Average wind speed

Average wind speed is the strongest in winter. While westerlies move to the north, the gale area is the strongest and most extensive all over the year. Average wind speed is between $6 \sim 11$ m/s in all winter. Trade wind reaches the strongest in July. Its average wind speed is between $7 \sim 10$ m/s. The smaller average wind speed of ≤ 6 m/s is observed in the middle of the Mozambique Channel. The smallest average wind speed is $4 \sim 6$ m/s in the tropical area east of 60° S and the Timor Sea. The average wind speed increases rapidly with latitude. The longest average wind speed all over the sea area is $9 \sim 12$ m/s to the south of 40° S. The galactic wind area with an average wind speed of ≥ 11 m/s is between $40^{\circ} \sim 50^{\circ}$ S, and $60^{\circ} \sim 100^{\circ}$ S.

3.1.3 Frequencies of forces ≥ 6 and 8 gales

Frequency of gale is very high in winter. Frequency of force ≥ 6 strong breeze higher than 10% is observed in the whole sea area. The force ≥ 8 fresh gale is observed hardly except in the westerlies $\geq 5\%$ all over the year. Frequency of force ≥ 6 gale is between $10\% \sim 40\%$ in the low latitude trade wind and monsoon area. The highest frequency of $\geq 20\%$ is observed between 10° S and 25° S, and frequency of $\geq 30\%$ at the center. The frequency between the Mozambique Channel and the tropical area is smaller in the western sea area and between $5\% \sim 10\%$. In the tropical area east of 60° S, the frequency is the smallest and between $0\% \sim 10\%$. Frequency of strong breeze is commonly between 20% and 50% to the south of 30° S. The isopleth of 25% is near 35° S and reaches 30° S northward in the eastern and western areas. The frequency of gales increases rapidly with latitude. It is higher than 30% to the south of 40° S and 35% to the south of 50° S. The frequency of 35% reaches the sea area to the north of 40° S in the middle of the sea area. Frequency of force ≥ 8 gales reaches the northernmost and the most extensive all over the year. It is higher than 5% in the whole sea area south of 40° S and locally 10% .

3.2 Alternation season

The wind field in the alternation season is similar to that in winter. Along with the westerlies moving to the south, all prevailing wind areas retreat to the south for 5 latitude degrees, the frequency reduces, the wind field starts to weaken and the gale area moves to the south.

3.2.1 Direction of prevailing wind

Westerly wind prevails to the south of 40° S and extends to 35° S with the frequency of wind direction between 40% and 70% . The wind direction is in disorder between $30^{\circ} \sim 35^{\circ}$ S. Frequency

of the southeast trade wind is as low as 70 % ~ 88 %. While the subtropical high moves to the south, the powerful trade wind area moves to the southeast. Frequency of southeast wind in the Mozambique Channel is higher than that in winter, between 60 % and 80 % in autumn and between 40 % and 50 % in spring. Westerly wind prevails in the sea area between 0° S and 5° S except in May, with the frequency of wind direction between 30 % and 47 %. Southeast wind dominates the tropical area west of the sea area under the influence of prevailing wind and landform. Frequency of wind direction is between 70 % and 96 %.

3.2.2 Average wind speed

In this period, while the subtropical high weakens and moves to the east, the average wind speed of the powerful trade wind area is evidently lower and 4 ~ 9 m/s mostly to the north of 40° S. In April, the average wind speed is the lowest. To the north of 40° S, the isopleth of ≥ 8 m/s is hardly observed. The average wind speed of ≤ 7 m/s is observed to the north of 20° S. While the latitude becomes lower and lower, the average wind speed reduces rapidly, ≤ 4 m/s in the tropical area and even ≤ 3 m/s in individual areas. It is almost similar to that in winter in the westerlies south of 40° S.

3.2.3 Frequencies of forces ≥ 6 and 8 gales

Frequency of strong breeze is lower evidently and its range reduces, moving to the south. Frequency of force ≥ 6 gales is between 5 % and 25 % to the north of 35° S, but ≤ 5 % in the trade wind area. The isopleth of 25 % is near 40° S and reaches near Africa 35° S. Therefore, both the frequency and the range southward are consistent with that in winter. The isopleth of frequency 5 % of force ≥ 8 gales is near 40° S approximately.

3.3 Summer period

In the summer period, while the subtropical high and westerlies retreat to the southernmost all over the year, and the wind field reaches the southernmost. The wind field is the weakest and the frequency of prevailing wind direction is the lowest all over the year. The area of gale reaches the southernmost. The average wind speed is the lowest all over the year. The frequency of gale is the lowest and its range is the smallest.

3.3.1 Direction of prevailing wind

The westerlies reaches the southernmost all over the year and affects the sea area to the south of 40° S. In January, the westerly wind dominates the south of 40° S with the frequency of wind direction between 50 % and 78 %. Wind direction between 30° S and 40° S is changeable. The southeast wind prevails between 10° S and 30° S. The trade wind area dwindles, reaching the weakest all over the year with frequency of wind direction as high as 60 % ~ 85 %. While the subtropical high moves to the south, the powerful trade wind area reaches the southernmost and the easternmost all over the year, concentrating between 15° ~ 25° S and 70° ~ 100° S. The south wind prevails in the west of Australia with frequency between 60 % and 90 %. The west wind dominates only in summer all over the year in the Timor Sea with frequency between 50 % and 60 %. The northwest-west wind which is in opposite direction in winter prevails in the monsoon wind area between 0° S and 10° S under the influence of strong northeast monsoon equator airflow with the frequency between 35 % and 50 %. The northeast-north wind prevails between the tropical area west of the sea area and the middle of the Mozambique Channel. Frequency of wind direction is 50 % ~ 80 %.

3.3.2 Average wind speed

In this period, the wind field is the weakest all over the year. Average wind speed in the high latitude area is stronger than that in low latitude, even 4 ~ 9 m/s to the north of 40° S. In January, the

isopleth of average wind speed of 8 m/s retreats southward to near 40° S. Distribution of average wind speed is similar to that in winter, but the range of gale with average wind speed ≥ 1 m/s contracts evidently. The average wind speed is 9 ~ 12 m/s between 45° ~ 55° S and 7 ~ 9 m/s to the south of 55° S. It is 4 ~ 8 m/s to the north of 40° S. In the powerful trade wind area it is higher than 7 m/s. The low latitude gale area is the outer sea area of Australia. The average wind speed is ≥ 8 m/s in a small region. The smaller average wind speed ≤ 6 m/s is observed in the subtropical high center. The smallest average wind speed ≤ 5 m/s is observed in most of the area between 0° S and 10° S and in the north of the Mozambique Channel. The average wind speed in the tropical area under the influence of strong monsoon equator airflow over the North Indian Ocean is bigger than 5 m/s generally , even bigger than 6 m/s.

3.3.3 Frequencies of gale ≥ 6 and 8 forces

Frequency of strong breeze is the lowest all over the year. It reduces evidently. Frequency of force ≥ 6 gale is 5 % ~ 10 % in the trade wind area, but ≤ 5 % in the monsoon area. The isopleth of 25 % is near 40° S. It reaches the south of 40° S northward in the east. The center of high frequency gale area is 45° ~ 55° S, with the requency of wind speed ≥ 40 % and the maximum of ≥ 45 %. Frequency of force ≥ 8 gale is very low and its range is the smallest, reaching the southernmost. In January, the isopleth of 5 % is interrupted into two small regions, *i.e.* the east of 60° S and near 40° E, 20° E.

Tab.1 Annual variation of the features of sea-surface wind in A, B and C areas

elements		months											
		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
A	average wind speed (m/s)	4.1	3.9	3.3	3.5	4.3	4.5	5	5.1	4.2	4.7	4.2	3.8
	frequency of Strong Breeze (%)	2	1	0	0	1	1	3	3	1	3	1	1
	frequency of Fresh Gale (%)	0	0	0	0	0	0	0	0	0	0	0	0
	most frequent win direction	N	N	W	W	S	SE	SE	SE	S	W	W	NW
B	average wind speed (m/s)	7.1	6.3	6.7	7.5	7.9	9	10.1	9.7	8.8	8.2	7.1	6.9
	frequency of Strong Breeze (%)	14	13	12	18	19	33	45	39	28	21	10	13
	frequency of Fresh Gale (%)	1	0	0	0	1	3	3	2	0	1	0	0
	most frequent win direction	E	E	E	E	E	SE	SEE	SEE	E	E	E	E
C	average wind speed (m/s)	10	9.7	10.1	10.5	10.5	12.8	13.5	11.6	11.9	10.8	10.2	9.3
	frequency of Strong Breeze (%)	43	42	46	47	30	68	73	56	60	48	42	36
	frequency of Fresh Gale (%)	4	5	6	11	6	14	25	12	14	8	7	3
	most frequent win direction	W	W	W	W	W	W	W	W	W	W	W	W

Note: A, B and C are meshes of 5° × 5° latitude and longitude as statistical grids, their longitude is from 65° E to 70° E. latitude of A is from 0° S to 5° S, latitude of B is from 15° S to 20° S, latitude of C is from 45° S to 50° S, their location is shown in Fig. 1.

4 Conclusion

(1) Wind field in the South Indian Ocean is similar all over the year. Wind direction basically goes

round anticlockwisely, centering around 35° S, 75° E. This center moves away 5 latitude degrees between WNW and ESE. It reaches the southernmost in summer and the northernmost in winter. It is more steady than that in the Northern Hemisphere. The circulation of the Indian Ocean is affected most by the surrounding continent among the circulations of global oceans. The region between 0° S and 10° S is controlled by the Indian monsoon. In summer, the westerlies reaches the southernmost all over the year. The westerly wind is observed to the south of 40° S. In winter, the westerly wind reaches 35° S that is the northernmost all over the year. The position is in the middle of them in the alternation season. Prevailing wind direction in the northwest under influence of prevailing wind and landform is different appreciably.

(2) Distribution of both average wind speed and frequency of strong breeze over the South Indian Ocean is bigger in high latitude area than that in low latitude area. Average wind speed is $4 \sim 11$ m/s all the year round. The smaller wind speed in the center of subtropical high is $5 \sim 7$ m/s. Wind speed is $4 \sim 10$ m/s at the center and $7 \sim 10$ m/s in powerful trade wind area at the bottom of subtropical high. Because the wind over the Mozambique Channel is blocked by Madagascar, the average wind speed is $4 \sim 7$ m/s. The smallest average wind speed of the South Indian Ocean is $4 \sim 6$ m/s in the tropical area east of 60° S. The average wind speed of westerlies is > 8 m/s and increases rapidly with latitude, the biggest between 45° S and 55° S and between 10 m/s and 12 m/s. Frequency of gale is very high throughout the year. Frequency of strong breeze force ≥ 6 higher than 10 % is observed in the whole sea area. The force ≥ 8 fresh gale is observed hardly except in the westerlies where it is ≥ 5 % all over the year.

(3) Seasonal difference of wind field elements over the South Indian Ocean is smaller than that in the Northern Hemisphere, but the biggest in the Southern Hemisphere. In the low latitude area, seasonal difference is more evident. While the westerlies moves to the north, the trade wind reaches the strongest in winter. Its average wind speed is $7 \sim 10$ m/s. The average wind speed in summer is $4 \sim 8$ m/s. Only in a small area in the outer sea west of Australia is it higher than 8 m/s. In winter, the frequency of the force ≥ 6 gale is 10 % $\sim$ 35 %. Only the frequency between the Mozambique Channel and the tropical area is smaller in the western sea area and between 5 % and 10 %. In the tropical area east of 60° S, the frequency is the smallest and between 0 % and 10 %. In summer, the frequency of gale reduces evidently. It is 5 % $\sim$ 10 % in the trade wind area, but ≤ 5 % in the monsoon area. The frequency of force ≥ 8 wind is lower than 5 % all over the year.

(4) The sea surface of the westerlies is very extensive. The monthly average wind speed is very high and the monthly mean frequencies of forces ≥ 6 and 8 gales are also bigger. Seasonal difference is very small. The average wind speed of westerlies is $8 \sim 12$ m/s. Frequency of force ≥ 6 gale is 25 % $\sim$ 50 %. Frequency of force ≥ 8 strong breeze is higher than 5 %. The seasonal swing of each element from south to north is evident. In winter, it reaches the northernmost. The isopleth of 25 % reaches 35° S, even 30° S in the east and west. In summer, it reaches the southernmost. The isopleth of 25% reaches 40° S and the south of 40° S in the east.

It should be noted that ship observation stations over the South Indian Ocean are absent especially to the south 50° S. Distribution of the four seasons and different sea areas is very uneven. Especially in the dangerous sea state and westerlies, ordinary ships evade these areas, so observation data about the extremum are lacking. Attention should be paid when these data are used.

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Distribution of Organic Matter, Iron, Manganese in Surface Sediments in the Nansha Islands Sea Area, South China Sea

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Abstract Concentrations of organic matter, iron and manganese in the deep sea surface sediments in the Nansha Islands sea area, South China Sea are measured. Horizontal and vertical distributions of iron and manganese are discussed. The vertical distribution of iron and manganese in the sediments results from reduction, diffusion, and redeposition of manganese (or iron) oxide and hydroxide in the sediment. There are the maxima of iron and manganese in solid phase in the top of the sediment, which is caused by the penetration of O_2 and the upward flux of Mn^{2+} (or Fe^{2+}). Manganese bacteria play a very important role in the cycle of solid-phase iron and manganese in the ocean environment. Manganese bacteria oxidize Mn^{2+} (or Fe^{2+}) in dissolved state to Mn^{4+} (or Fe^{3+}) in oxidized state under the aerobic condition, whereas they reduce iron and manganese in anaerobic conditions.

Keywords organic mater, iron, manganese, surface sediment, Nansha Islands sea area, South China Sea

1 Introduction

Physical and chemical changes of particles such as terrigenous clay, authigenic minerals and clay etc. in the seawater, especially in the sediment, are called diagenesis^[1]. Diagenesis of organic matter means the changes of chemical composition of organic compounds. The physical and chemical properties of pore water and solid phase experiences great changes in the surface sediments during diagenesis processes. Chemical constituents are exchanged with the overlying water by way of diffusion, biogenic and physical disturbances. Understanding the diagenesis process of sediment is important in comprehending the biogeochemical cycle of elements.

The research on marine sediment environment hinges on the system of sediment, pore water and water column. Iron and manganese are the key metals of the sediment redox system. In recent years, much attention has been paid to the behavior of the iron, manganese and other accompanying elements. They emphasize the dissolution, transport and deposition of iron and manganese under different pH, especially under continuously changing redox conditions. The behavior of redox of iron and manganese is typical in sediments, and their reactions during diagenesis are obvious. Wangersky *et al.* (1965) indicated that Mn^{2+} is combined into particulate organic matter and released at the bottom of water column after the organics are utilized by organisms^[2]. It is one of the key mechanisms of enrichment of manganese at the interface of sediment and seawater. Little research has been done on the early diagenesis of iron and manganese in the deep-water basin of Nansha Islands sea area due to sampling difficulty. Our research focuses on organic matter, iron and manganese, and attempts to illustrate their

biogeochemical processes, which provides the baseline conditions of sediment environment in this sea area.

2 Materials and methods

Two cruises on board the ship "Experiment 3" were carried out in the Nansha Islands sea area in winter 1997 and in summer 1999. Surface sediment samples were collected by crab corer at 9 stations and 8 stations, respectively, during the two cruises (Fig. 1). Water depth of each station is listed in Tab.1. Almost all the samples are grey mud. Subcores (5cm in diameter) were taken by placing plastic tubes in the corer where the surface sediments were not disturbed. The sediments were subsampled and weighed on board the ship immediately. Samples were dried at 50 °C for 24 h in the lab. Dried samples were grounded, then passed through a sieve of 180 μ m mesh and stored in a drier. Pore water nutrients of the same station were reported elsewhere^[3].

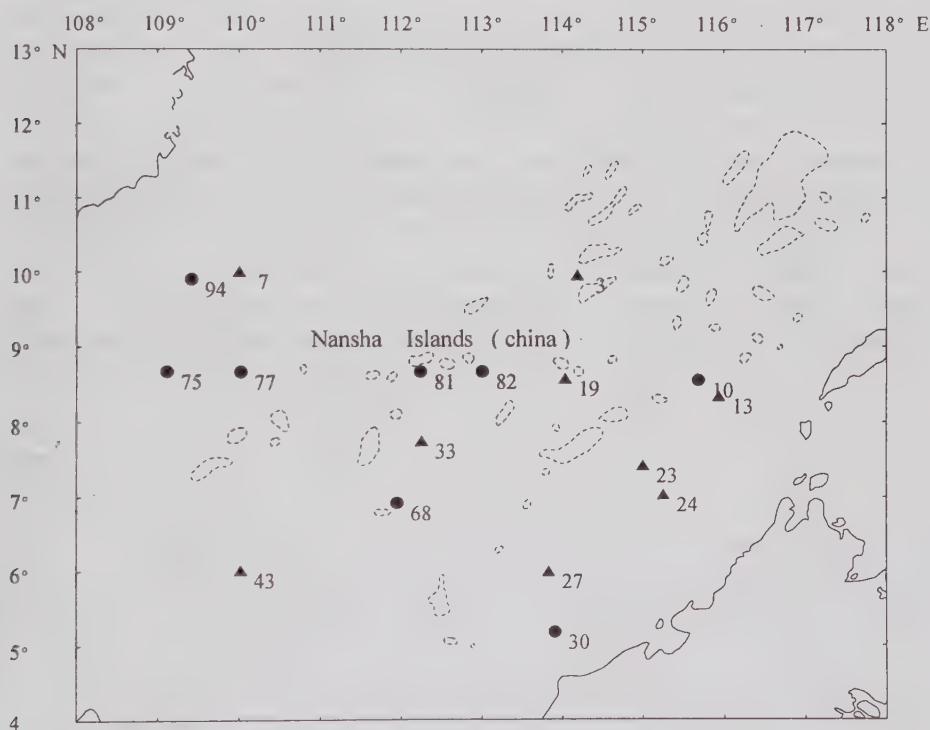


Fig. 1 Sediment sampling stations in Nansha Islands sea area, South China Sea
(▲ Winter cruise of 1997, ● Summer cruise of 1999)

The finely processed sediments were burned to ashes at 400 °C for 4 h and were weighed before and after burning. The losing weight was defined approximately as the content of the organic matter. The ashed sample 0.1 g was dissolved with fluohydric acid and sulfuric acid and digested with nitric acid. Digests were analyzed for iron by o-phenanthroline spectrophotometry and for manganese by ammonium

peroxydisulfate spectrophotometry. The samples were analyzed using 722 s spectrophotometer. The error is less than $\pm 5\%$ for both iron and manganese.

$\text{Fe}_2\text{O}_3\%$ (or $\text{MnO}\%$) = $(W \times 10^{-6} / G) \times 100$, where W stands for microgramme of Fe_2O_3 or MnO , G stands for the amount of the sample (The amount of sample used for iron and manganese in this report is 0.02 g).

3 Results and discussion

3.1 Organic matter, iron and manganese in the sediment

The mean contents of organic matter, iron and manganese in the sediments are presented in Table 1. The mean contents of organic matter, iron and manganese were 6.97 %, 3.73 %, 1.42 %, respectively, in the winter 1997 and were 7.86 %, 3.71 & 1.49 %, respectively, in the summer 1999. The content of organic matter and MnO from station 43, 75, 94 where the sediment is sandy is lower than that of other stations where the sediment is muddy. The lower content of organic matter at those sandy stations might be due to the fact that the sediment porosity here is high^[3], the water is shallow, and oxygen concentration in the sediment is relatively high, which induces more celerity of organic matter decomposition on the surface sediment. The low content of MnO is mainly caused by the weak ability of bacterial metabolization and solubilization for such types of sediment.

Fig. 2 represents correlation between the mean content of iron or manganese and water depth. Basically, manganese increases with the depth, and the stations of high concentrations of manganese are located in the deep-sea basin, while the stations of low concentration are located in the shelf near shore. For example, the abundance of manganese (see in Tab. 1) is low for Stations 23, 24, 30, 75, 94, which is similar to the abundance of Chinese nearshore sediment, indicating their terrigenous characters. The result is consistent with that of Wang *et al.* (1991)^[4]. However, manganese in the deep-sea sediment is obviously high (Tab. 2). The content of iron is not influenced by the water depth and distance form the shore.

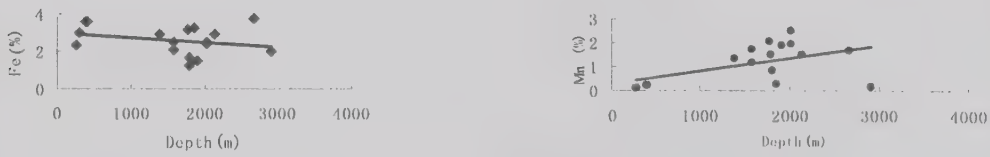


Fig. 2 Contents of Fe and Mn versus the water depth

Tab. 1 Abundances of Fe and Mn in different sea area sediments

Abundance	Mean of near shore*	Shelf of Nansha	South China sea	Shallow sea of China	Trough of Chongsheng	Deep sea clay
Fe%	2.85	—	2.87	3.10	3.00	6.50
Mn%	0.17	0.048	0.049	0.053	0.202	0.67
Reference	This study	Ref.[4]	Ref.[5]	Ref.[5]	Ref.[5]	Ref.[6]

*Mean content of Stations 23, 24, 30, 75, and 94

**Tab. 2 Mean losing weight after burning (organic matter) and the contents of Fe₂O₃, MnO
in the surface sediment**

Station	Depth (m)	Organic matter (%)	Fe ₂ O ₃ (%)	MnO (%)	Fe (%)	Mn (%)
3	1 804	6.61	1.76	1.06	1.23	0.82
7	1 795	6.40	2.34	1.91	1.64	1.48
13	2 145	8.83	4.11	1.96	2.88	1.52
19	1 590	5.79	2.94	2.22	2.06	1.72
23	2 906	7.06	2.86	0.20	2.00	0.16
24	1 862	6.78	4.68	0.39	3.28	0.30
27	2 674	8.65	5.32	2.12	3.72	1.64
33	1 775	9.14	4.47	2.64	3.13	2.05
43	410	3.46	5.07	0.28	3.55	0.22
10	1 911	6.67	2.15	2.46	1.51	1.90
30	395	9.38	5.15	0.26	3.61	0.20
68	2 024	10.07	3.60	3.23	2.52	2.50
75	265	4.39	3.36	0.13	2.35	0.10
77	1 585	9.11	3.53	1.50	2.47	1.16
81	1 395	8.69	4.14	1.76	2.90	1.36
82	2 027	9.23	3.48	2.49	2.44	1.93
94	289	5.33	4.27	0.11	2.99	0.09
Mean of 1997	—	6.97	3.73	1.42	2.61	1.10
Mean of 1999	—	7.86	3.71	1.49	2.60	1.16
Average of all	—	7.42	3.72	1.46	2.61	1.13

3. 2 Horizontal distribution of iron and manganese

The contour lines of iron are almost parallel to the coastline near Pulau Kalimantan (Fig. 3a). The concentrations of iron decrease gradually from the continental shelf to the open sea. High contents of iron nodules and ferro-clays lead to high concentrations of Fe₂O₃ in the sediment of the continental shelf. Iron concentrations increase a little in the deep-water basin in the center of Nansha Island sea area. This distribution pattern matches the result of Chen S M *et al.* (1993)^[7]. The lowest zone lies in the area full of carbonate sediment, the iron concentration is lower than 2 %, as calcium carbonate can reach 91.18 % here (The Multidisciplinary Oceanographic Expedition Team of Academia Sinica to Nansha Islands, 1993)^[8]. The distribution of iron in the northern South China Sea are similar^[9, 10].

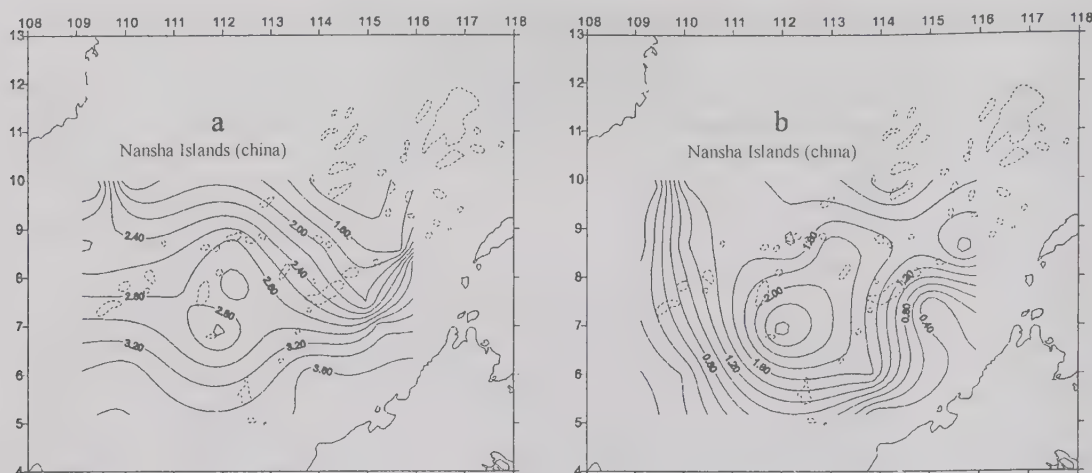


Fig. 3 Horizontal distribution of mean contents of iron (a) and manganese (b)

The horizontal distribution of manganese shows that the contents increase from the shore to deep-sea basin, and there is a high content zone in the center of the Nansha Islands sea area, which has abundant micro-manganese nodules. There are three high concentration zones of micro-manganese in this sea area: one is down the continental slope of deep-sea basin in the northwest part, the second one is in the middle continental slope of the submarine plateau in the southwest part, and the last one is down the continental slope of the trough south of the middle part^[11]. The oxidation-reduction potential is comparatively high in the deep-sea sediment where the ferro-manganese oxide colloids and nodules are formed, and therefore, the contents of metals such as manganese are higher than other sea areas^[8]. The contour lines are parallel with the shore coastline due to the fact that the deposition of manganese is associated with the granule sediment.

3.3 Vertical distribution of organic matter, iron and manganese

Inorganic carbon, nitrogen and phosphorous are synthesized into organic matter through photosynthesis in the surface water column. Only small parts of particulate organic matter enter the sediment. Vertical profiles of organic matter, iron and manganese of two typical stations are shown in Fig. 4. The concentration of organic matter represented here decreases with depth, which reflects the decomposition of organic matter. Froelich *et al.* (1979) found that dissolved oxygen could be worn out gradually from the surface layer to up few centimeters and the sediments turned into the suboxic zone as the decomposition of organic matter is slow^[12]. At the top of the sediment, there is a maximum of manganese near 1 cm and 3 cm at Stations 13 and 33, respectively. A high concentration of iron is also found in the region at 5 cm, and from 0 to 5 cm the concentration is relatively high. The appearance of high concentration of iron and manganese in the top layer of sediment cores is the result of upward flux of Fe^{2+} and Mn^{2+} and their redeposition^[12].

Downward flux of O_2 and upward flux of Mn^{2+} together determine the depth of high concentration of manganese. O_2 and Mn^{2+} are both consumed in this zone. Otherwise, the redundant O_2 would diffuse downwards to oxidize Mn^{2+} to move the enrichment zone of manganese down. At the same time, the redundant of Mn^{2+} would diffuse upwards to push the enrichment zone of manganese up. The system

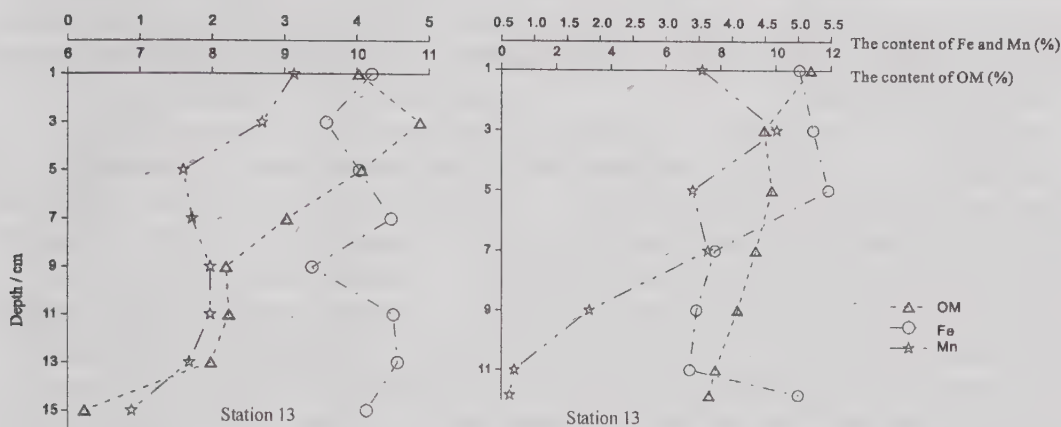
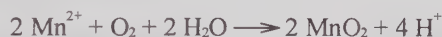


Fig. 4 Vertical distribution of organic matter, Fe and Mn

will be stable only when the flux of Mn^{2+} downward is double of O_2 , which is diffused upwards. The reaction equation can be described as follows:



Stumm *et al.* (1970) described the oxidation and deposition chemistry of iron and manganese in the natural environment^[13]. Mn^{2+} is oxidized into MnO_2 due to the catalysis of reaction exterior. Then, MnO_2 absorbs the redundant Fe^{2+} or Mn^{2+} , which is in turn oxidized subsequently. The distributions of iron and manganese are likely to show that they exist in the form of oxides and hydroxides in the surface sediment. Enrichment of iron and manganese in the surface layer is induced by deoxidization of iron or manganese (hydr)oxides. Vertical distributions of iron and manganese in the sediment of the sea area are resulted from reduction, diffusion, and redeposition of iron or manganese oxides and hydroxides in sediment.

3.4 Transport of iron and manganese ions by bacteria

The ocean is a vast microorganism pool, which can accelerate many chemical changes and diagenesis. The activity of microorganism changes with sedimentation of suspending particles (including organic matter and inorganic matter) from the water column to the sediment, and they can shift the direction of redox potential, and participate in the transformation of metal elements^[14]. In the Nansha Islands sea area, the vertical distribution of iron and manganese (Fig. 4) in the surface sediment shows that the concentrations of iron and manganese in the sublayer are much lower than those in the surface layer. It is related with reducing the high valence state of metal ions to low valence state ions that reenter the soluble phase in anaerobic conditions. Activities of bacteria influence the composition of pore water and solid phase of sediment. Biogeochemical factors play a very important role in the main phase of the formation of iron-manganese nodules.

Metabolism of bacteria and their products affect the pelagic depositional environment in the Nansha Islands sea area. Many marine sedimentary chemical processes are associated with bacteria. Shi *et al.* (1998) set up manganese bacteria to grow and propagate in the culture medium, which contains Mn^{2+} , and found that Mn^{2+} is oxidized continuously^[15]. It is shown that the growth of manganese bacteria accelerate the oxidization of bivalent manganese. Most Mn^{2+} in the solution is oxidized into Mn^{4+} with

time. Manganese bacteria act as a catalyzer to accelerate the transformation of iron and manganese ions effectively. This kind of bacteria is active for the diagenesis of iron and manganese in the sediment of the Nansha Islands sea area.

In the system of overlying water — sediment — microorganism, iron, manganese and other metals are deposited after being oxidized by manganese bacteria under the oxic condition. The metals such as iron and manganese form hydroxide precipitation and are deposited into the solid phase. Furthermore, the growth and increase of manganese bacteria increase pH of the media, which is propitious to colloidal ferric hydroxide to absorb Mn^{2+} . Through such a pathway, manganese bacteria can oxidize Mn^{2+} to manganese oxide easily, and then, the iron and manganese in the ocean can deposit and be enriched slowly. Under the anaerobic environment, the manganese bacteria can improve the solubilization of iron and manganese in the bottom of the sediment core. The high valence state of metal ions can be reduced to low valence state soluble ions, and they can be transported into pore water and overlying water. So the process of oxidized deposition, reduction-dissolution and re-oxidized deposition takes place and it may be one of the reasons that metals distribute mainly in the surface of the sediment but are not buried by the sinking particles^[14]. Microorganisms, especially manganese bacteria, are important for the cycle of iron and manganese in the ocean environment. Manganese bacteria can oxidize iron and manganese, which are then deposited onto particles in aerobic conditions, whereas they reduce Mn^{4+} (or Fe^{3+}) in indissolved state to Mn^{2+} (or Fe^{2+}) in dissolved state under anaerobic condition. And again, iron and manganese redeposit and re-enrich when encountering an oxidative environment. Microorganism is one of the key factors to the ore-forming process of the metals in the ocean bottom.

4 Conclusion

The mean content of organic matter, iron and manganese in the sediment of the Nansha Islands sea area was 6.97 %, 2.61 %, 1.10 % in the winter cruise of 1997 and 7.86 %, 2.60 %, 1.16 % in the summer cruise of 1999, respectively. Basically, manganese increases with the depth in the sediment cores. The abundance of manganese is much lower at the stations near terrene such as Stations 23, 24, 30, 75 and 94, the values are close to those for the continental shelf and adjacent sea of China, showing their terrigenous property. The water column depth and the distance from the shore do not affect the contents of iron on the whole.

A high concentration of manganese zone appears in the center of Nansha Islands sea area. Based on the horizontal distribution of iron and manganese we discover that the contour lines are nearly parallel to the coastline.

Organic matter decreases with the depth. Manganese concentrations reach the maximum at 1 cm and 3 cm in the top of the surface sediment at Stations 13 and 33, respectively. At Station 33, iron also has a high concentration zone at 5 cm. Such a distribution is believed to be caused by upward diffusion and redeposition of Mn^{2+} (or Fe^{2+}). Under aerobic and anaerobic environment, the process of oxidization, reduction and deposition of iron and manganese forms the high concentration of them in the top layer in the solid phase.

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Spatial Distribution of Polychlorinated Biphenyls (PCBs) Contaminants in the Tidal-flat Sediments of Yangtze Estuary

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Abstract PCBs pollutants are measured on tidal-flat sediments of Yangtze estuary by a high resolution capillary column gas chromatography (HP6890) equipped with an ⁶³Ni electron capture detector (ECD). The concentration tendency of PCBs is *Phragmites* zone > *Scirpus* zone > bare mudflats. There are linear relations between PCBs and TOC and > 63 μ m grain size percentage (in volume). The low chlorinated congeners may be more important than the high chlorinated congeners in this area. PCBs prefer to accumulate in the sediments near sewage outlets and *Phragmites* zone. The sediments' PCBs pollution (10.7 ~ 28.6 ng/g, dry weight) in the Yangtze estuary tidal-flat is less serious than that of the most of other areas in the world. But the detected ratio is 100 %, even the Jiuduansha shoal has detected PCBs, so much attention should be paid to this area for PCBs.

Keywords Polychlorinated Biphenyls (PCBs), tidal-flat sediments, spatial distribution, Yangtze estuary

1 Introduction

Yangtze River estuary is the biggest one in China, and there are domestic and manufactural rubbish disposal sites for Shanghai city in this tidal-flat. The Shanghai city, the whole Yangtze delta, or even all the Yangtze basin, will be PCBs contaminant sources of Yangtze estuary tidal-flat^[1]. According to literatures so far, only two investigations for waters have included PCBs in the Yangtze estuary^[2,3]. No PCBs pollution of the tidal-flat sediments has been reported so far.

In this paper, the PCBs concentration is measured, its influence factors are analyzed on the Yangtze estuary tidal-flat sediments, and some most important information has been obtained: Compared with other places in China and even all over the world, the pollution (10.7 ~ 28.6 ng/g, dry weight) of PCBs in the Yangtze estuary is less serious, and even much less than the national criterion for PCBs (50 mg/kg, GB13015-91) of the State Environmental Protection Administration, but the detection ratio is 100 %, and even in the Jiuduansha, a neonatal shoal in Yangtze estuary, where there is little effect from human activities, PCBs has been detected, so much attention should be paid to this area for PCBs.

2 Material and methods

2.1 The time, location and methods for sampling

Eleven tidal-flat surficial (0 ~ 5 cm) sediment samples are collected from this study area in 2000, including 7 sampling areas: Bailonggang, Chaoyang, Donghai, Jiuduansha shoal, Luchaogang, Laogang and Liuhekou, 4 of them from *Phragmites* zone (at the highest part of the inter-tidal zone), 4 from *Scripus* zone (middle tidal-flat), the rest from bare mudflat (low tidal-flat). Sampling locations are showed in Fig. 1.



Fig. 1 Location of samples collected in the Yangtze Estuary tidal-flat

By using stainless steel spades, tidal-flat surficial (0 ~ 5 cm) sediment samples are picked and put into sealed plastic bags in field, air-dried at room temperature in lab., then smashed (but not destroying the natural shape of particles) with agate mortar and pestle and sieved (nylon sieve, No.80 U.S.A. *i.e.* hole diameter 0.177 mm), and kept in sealed plastic bags for measuring.

2.2 Reagents

All reagents (acetone, hexane *etc.*) are A.R. (analytical reagent) purity, and the standard sample is bought from Supelco, U.S.A..

2.3 PCBs extraction

2~5 g dry sample is soxhlet extracted for 20 ~ 24 h with 40 mL acetone and 80 mL hexane, then extracted twice with hexane. Add copper to remove element sulphur, put the extraction liquid from many times into one container, and slowly concentrate the extraction liquid in highly pure nitrogen gas current. Elute the concentrated liquid with 2 % deactivated aluminum column. At last, elutriate it with 100 mL hexane, and then extract the liquid.

2.4 PCBs analysis

PCB is analyzed on a high resolution capillary column gas chromatography (HP6890 gas

chromatography) equipped with an ^{63}Ni electron capture detector (ECD). The chromatographic column is PH-5 capillary column ($30\text{ m} \times 0.32\text{ mm} \times 0.25\text{ }\mu\text{m}$). Keep the column temperature at $80\text{ }^{\circ}\text{C}$ for 2 min, then elevate the temperature to $160\text{ }^{\circ}\text{C}$ at the ratio of $10\text{ }^{\circ}\text{C}/\text{min}$, then to $190\text{ }^{\circ}\text{C}$ at $1.5\text{ }^{\circ}\text{C}/\text{min}$, at last to $256\text{ }^{\circ}\text{C}$ at $2\text{ }^{\circ}\text{C}/\text{min}$ and keep it for 6 min. The highly pure nitrogen gas serves as the carrier gas, the temperatures of inhaler and detector are $260\text{ }^{\circ}\text{C}$ and $330\text{ }^{\circ}\text{C}$ respectively. Aroclor 1 232 is added to the samples prior to extraction to act as an internal standard and to monitor recovery efficiency. One blank sample* is analyzed for comparison. It is from Chongmingdao Island at the depth of 38 m in $121^{\circ} 26' 26''\text{ E}$, $31^{\circ} 47' 07''\text{ N}$ (by GPS) and the sediment sample is from geological history, with no PCBs in it. Chromatogram of GC-ECD in Fig. 2 shows the typical samples PCBs concentration.

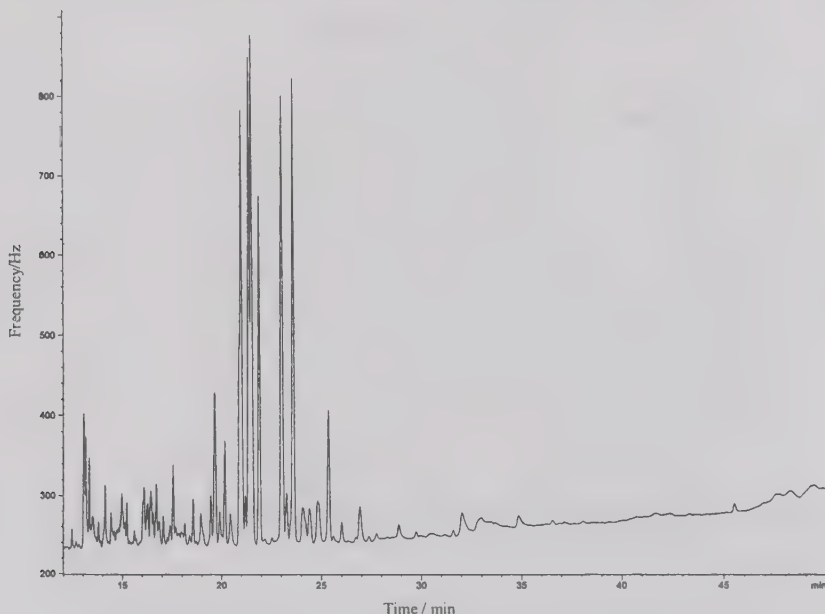


Fig. 2 Chromatogram of GC-ECD (Samples are collected from Bailonggang, No.BLG3)

2.5 Determination of other parameters

The grain size analysis on sediments is made with the laser granularity instrument (LS100Q), the total organic carbon (TOC) of sediments is determined by the muffle stove, and the ignition loss of organic (ILO) substitutes for $\text{TOC}^{[4]}$.

3 Results and discussion

3.1 PCBs concentration and its sources

Polychlorinated Biphenyls (PCBs) total concentration in the Yangtze estuary tidal-flat sediments is shown in Fig. 3. The average PCBs concentration is 18.12 ng/g (dry weight), with the maximum value 28.6 ng/g occurring in the big sewage outlet (near Bailonggang harbor) tidal-flat sediment. It should be

*sample from Prof. Liu Cangzi, State Key Laboratory of Estuarine and Coastal Research, ECNU, P. R. China

noted that the detection ratio is 100 %, in the neonatal estuarine shoal Jiuduansha with the sediments' PCBs concentration circa 10 ng/g, where human activity is much less intensive.

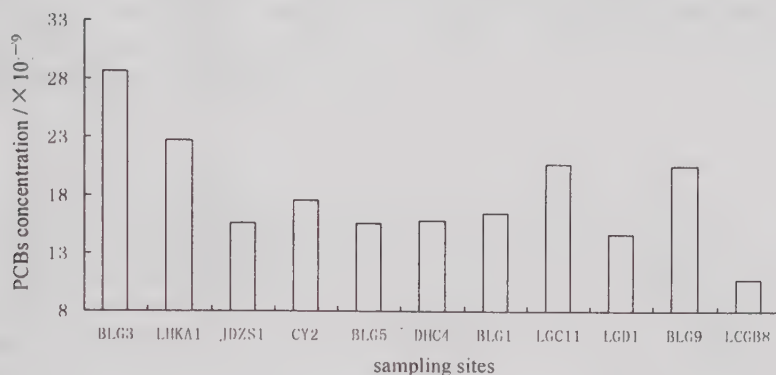


Fig. 3 PCBs concentration in the sediments of Yangtze Estuary tidal-flat

There are 4 spatial sources of PCBs for Yangtze estuary tidal-flat sediment: pollution is brought from drained sewage alongshore; from upstream upriver waters of Yangtze River; from sea by tide and wave; and solid fall from air *etc.*. The maximum value of PCBs concentration occurs near the sewage outlet, indicating that sewage draining is the most important source of PCBs pollution in this area. Secondly, river source of PCBs pollution shows outstanding effects. J. Chen *et al.* (1999) analyzed the sediments in the Wuhan and Nanjing sections of the Yangtze River, where the PCBs concentrations were 20 and 14 ng/g respectively^[5]. X. Jiang *et al.* (2000) analyzed PCBs in water and suspended particles at the Nanjing sections of the Yangtze River, where PCBs concentrations are 1.22 ~ 2.48 ng/L and 2.94 ~ 25.23 ng/g respectively^[6], and PCBs distributes between the dissolved phase and the suspended particle phase, the dissolved phase being 61 % ~ 78 %. Thirdly, the source from sea water is also important^[2, 3]. Lastly, PCBs from particle fall from air in tidal-flat sediments still needs more research, but according to the transferred properties and recent studies on it, we can guess that the part of particle fall from air in the total PCBs is not very important.

3.2 PCBs spatial distribution factors

In the Yangtze estuary tidal-flat, PCBs distribution factors are complex, with the maximum value occurring in the *Phragmites* zone near the sewage outlet, and the minimum in the bare mudflat on the artificial peninsula of Luchaogang. The difference of PCBs concentration is obvious between sampling areas.

Firstly, the tidal-flat micro-geomorphology affects the spatial distribution of PCBs. PCBs concentration is in the order of: *Phragmites* zone (high tidal-flat) > *Scirpus* zone (middle tidal-flat) > bare mudflat (low tidal-flat), the average values being 21.13, 17.20, and 15.33 ng/g respectively. There are many differences between sedimental environment and sediments with different geomorphological parts. For example, sediment TOC concentration is *Phragmites* zone > *Scirpus* zone > bare mudflat. The hydrodynamic condition in the *Phragmites* zone is weaker than that of *Scirpus* zone and bare mudflat, so more favorable for the sedimentation of finer grains and particle-reactive PCBs. Grain size analysis shows: the sediments median grain sizes are in the order of *Phragmites* zone < *Scirpus* zone <

bare mudflat, average values being 9.77, 9.86 and 13.24 μm respectively. PCBs accumulates more easily in the weak hydrodynamic geomorphological part, *i.e.* *Phragmites* zone.

Secondly, correlation analysis shows that there is an obvious linear tendency between TOC and PCBs concentration (see Fig. 4).

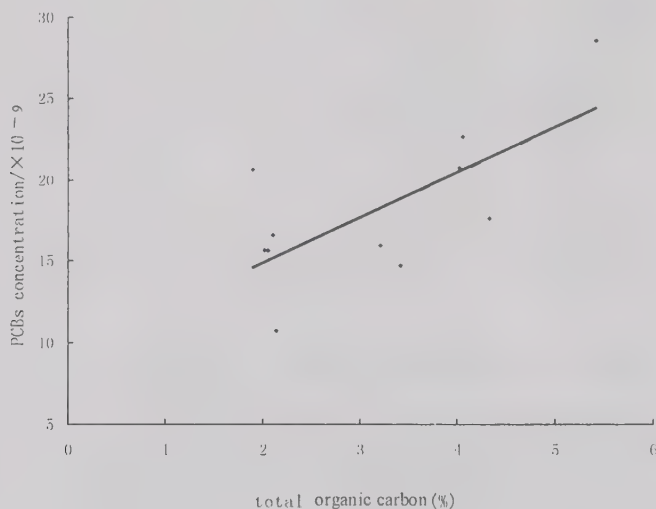


Fig. 4 Scatter diagram of PCBs vs. TOC

Thirdly, the grain size of sediment samples affects PCBs too. According to the laser grain size analysis in this study, correlation analysis between grain size parameters and PCBs shows: correlation between PCBs and percentage of particle volume on $> 63 \mu\text{m}$ (V/V %) is strongest among other main grain size parameters (*i.e.* median grain size, peak value grain size, average grain size), the correlation coefficient being 0.6817. PCBs and other grain size parameters have no correlation. According to J. Chen *et al.* (1999), Pierard C. *et al.* (1996), S.Chu and X. Xu *et al.* (1995), the relation between PCBs and grain size parameter in Yangtze estuary tidal-flat sediments, maybe mainly results from the low chlorinated congeners in the Yangtze estuary tidal-flat^[5, 7, 8].

4 Conclusion

It is concluded from this study: there are 4 spatial sources of PCBs for Yangtze estuary tidal-flat sediment: the contaminants are brought from the drained sewage alongshore; from upstream waters of Yangtze River; from sea by tide and wave; and solid fall from air *etc.* PCBs prefer to accumulate in the sediments near the sewage outlet and *Phragmites* zone. The geomorphological tendency of PCBs concentration is *Phragmites* zone $>$ *Scirpus* zone $>$ bare mudflats. There are linear relations between PCBs and TOC, and $> 63 \mu\text{m}$ grain size percentage (in volume). The low chlorinated congeners may be more important than the high chlorinated congeners in this area. The sediments' PCBs pollution (10.7 ~ 28.6 ng/g, dry weight) in the Yangtze estuary tidal-flat is less serious than that in most of other areas in the world^[5-7, 9-24]. But the detection ratio is 100 %, so we should pay much attention to this study area. In order to understand and prevent the harmfulness of PCBs pollution, further study should be made on the concentration of chlorinated congeners in the tidal flat sediments.

Acknowledgements

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Petrology, Geochemistry and Nd-Sr-Pb Isotopic Properties of Volcanic Rocks in Daheishan Island, Penglai, Shandong Province

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Abstract The major elements, trace elements, K-Ar age and Sr-Nd-Pb isotopic systems of the Cenozoic volcanic rocks in Daheishan Island and Cishan, Penglai, Shandong Province are measured. The volcanic rocks (olivine-nephelinite and nepheline-basanite) in Daheishan Island erupted periodically in an interval of 0.32 Ma, from 8.72 Ma, 8.39 Ma, 8.08 Ma to 7.73 Ma. The volcanic rocks are all rich in light REEs. They are similar to the OIB-type alkali basalt in the trace elements normalized model by primordial mantle: rich in high field elements such as Nb and Ta, and incompatible elements such as Cs, Rb, Ba, Th, U. The volcanic rocks show a depletion of K and Rb elements. It is suggested by the trace elements that the olivine-nephelinite in Daheishan Island is originated from deep resources under the continental mantle. $\epsilon_{\text{Nd}}(0)$ values of the volcanic rocks in Daheishan Island and Cishan are 5.31 ~ 8.51 and 7.33 respectively, suggesting that the volcanic rocks are from the depleted mantle resources, which have higher Sm/Nd ratios than the CHUR. $^{143}\text{Nd} / ^{144}\text{Nd}$ ratios of Daheishan Island olivine-nephelinite and Cishan alkali basalts are 0.512 910 ~ 0.513 074 and 0.513 014 respectively. The $^{87}\text{Sr} / ^{86}\text{Sr}$ of Daheishan Island volcanic rocks are lower than that of Cishan, 0.703 427 ~ 0.703 482 and 0.703 895 respectively. The Daheishan Island olivine-nephelinite has the Pb isotopic values as follows: $^{206}\text{Pb} / ^{204}\text{Pb} = 18.028\ 9 \sim 17.972\ 8$, $^{207}\text{Pb} / ^{204}\text{Pb} = 15.435\ 8 \sim 15.402\ 2$ and $^{208}\text{Pb} / ^{204}\text{Pb} = 38.087\ 6 \sim 37.997\ 5$, lower than those of Cishan basanite. The Cishan basanite has $^{206}\text{Pb} / ^{204}\text{Pb} = 18.240\ 1$, $^{207}\text{Pb} / ^{204}\text{Pb} = 15.564\ 5$ and $^{208}\text{Pb} / ^{204}\text{Pb} = 38.535$. The authors suggest that the olivine-nephelinite in Daheishan Island is similar to the E-type MORB or Hawaii OIB, and the alkali basalts in Cishan similar to the Kerguelen OIB. The dominant mantle components of DM+PREMA and perhaps DM (Dupal type) are the dominant mantle components for volcanic rocks in Daheishan Island and Cishan. The PREMA component plays an important role.

Keywords Daheishan Island, Penglai, Cenozoic volcanic rocks, K-Ar age, DM, PREMA

1 Introduction

There occur Cenozoic volcanic rocks in Wuliqiao-Cishan and Daheishan Island of Penglai City, Shandong Province (Fig. 1). They are emplaced in a rift system formed in response to the subduction of the western Pacific plate beneath the eastern Asiatic continental margin. It is nearly in the centre of the rift system. In the northeastern and eastern China, there are many Cenozoic volcanic centers such as Kuandian, Changbaishan and Wudalianchi respectively in the Liaoning, Jilin and Heilongjiang Provinces, and Mingxi in the Fujian Province^[1-3].

For the alkaline basalt in Wuliqiao-Cishan, many studies on the petrology, geochemistry,

chronology and isotopic systems have been carried out^[4-10]. However, only a preliminary geological survey^[11] and a K-Ar age (transferred from Liu et al., 1992)^[12] have been got for the volcanic rocks in Daheishan Island.

In this paper, the major elements, K-Ar age, trace elements and Sr, Nd and Pb isotopic systems are measured for the volcanic rocks. And this paper discusses the mantle reservoirs for both the volcanic rocks.

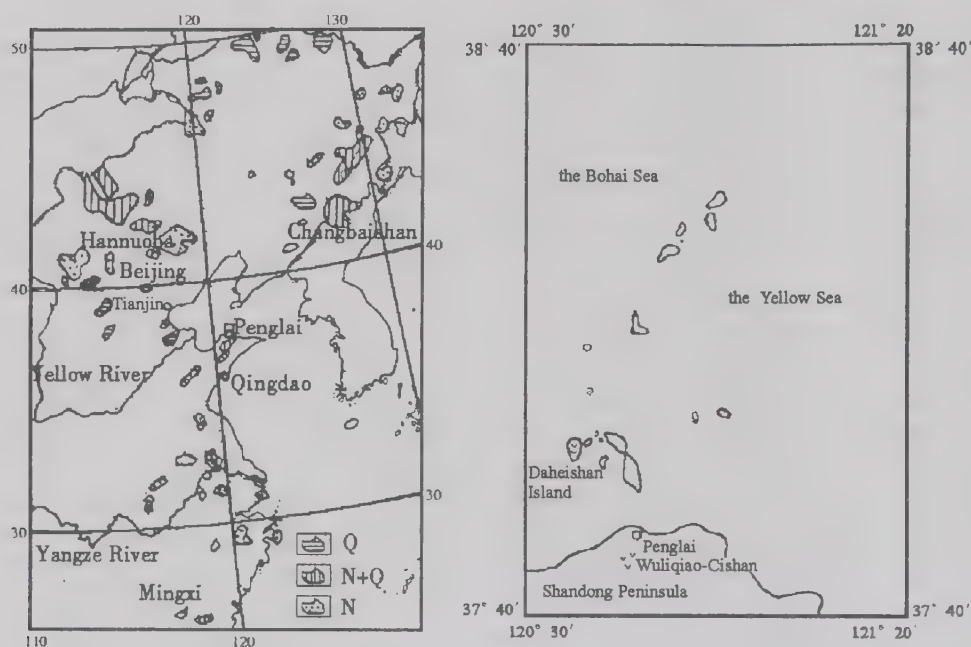


Fig. 1 Cenozoic volcanic rocks in the eastern China. Daheishan Island and Cishan volcanic rocks in Penglai, Shandong Province are showed

2 Outcrop of Cenozoic volcanic rocks in Daheishan Island

Cenozoic volcanic rocks occur in the northwest of Daheishan Island. Actually it is a hill of volcanic rocks (Fig. 2a). The rocks on the hill are compact and spherical (Fig. 2b). There are two layers of volcanic rocks on outcrop respectively above and beneath the brick-red roasted layer (Fig. 2c). The rocks in the upper layer are compact, while those in the lower layer are rich in gas-vents. There is black alkaline basalt full of gas-vents intruded in the roasted layer. The olivine inclusions from deep mantle are seen in the rocks (Fig. 2d).

Compact specimens 01420H-1, 01420H-3 and 02526H-6 are sampled in the layer above the roasted layer in Daheishan Island. Specimens 02526H-3 and 02526H-4 are sampled 0.5 m beneath the roasted layer. Specimens 02526H-2 and 02526H-5 are sampled in the roasted layer.

Sample 01419PW-3 is gained from the Wuliqiao-Cishan volcanic rocks.

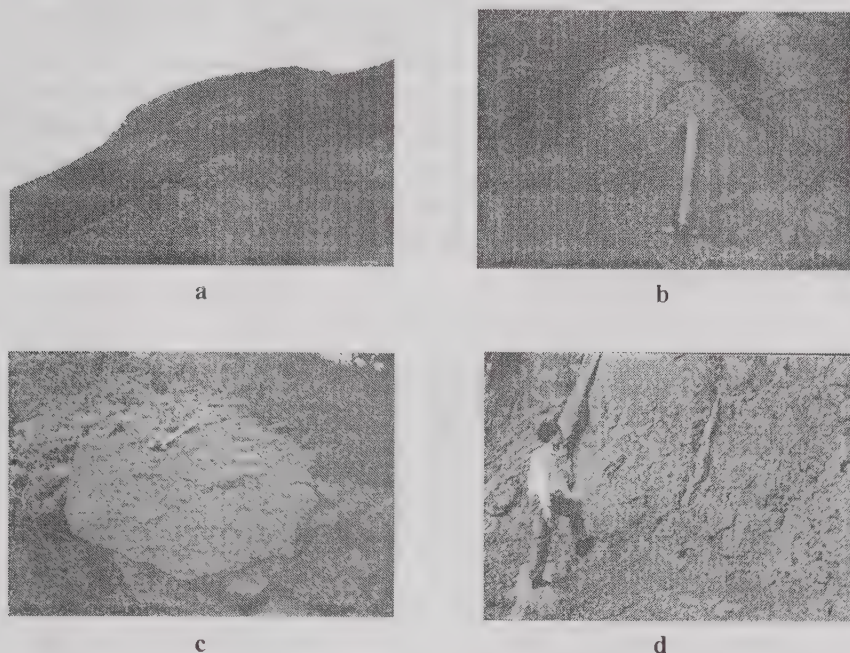


Fig. 2 The occurrence of volcanic rocks in Daheishan Island, Penglai, Shandong Province
 a, a hill of volcanic rocks; b, spherical volcanic rocks; c, compact rocks above the brick-red roasted layer, while those in the lower layer are rich in gas-vents. There is black alkaline basalt full of gas-vents intruded in the roasted layer; d, the olivine inclusions from deep mantle are seen in the rocks.

3 Major elements of the volcanic rocks in Daheishan Island and Cishan

3.1 Methods and results of major elements and mineral compositions measurement

Samples 01420H-1 and 01420H-3 from Daheishan Island, and samples 01419-PW-3 from Cishan are analyzed with the X-Ray fluorescence spectrometry (XRF) at the Institute of Geology and Geophysics, Chinese Academy of Sciences (CAS), using an apparatus of Philips PW 1400. Samples 02526H-2, H-3, H-4, H-5 and H-6 are measured with the weight method at the Laboratory of Geology and Mineral Resources Bureau of Hebei Province in Langfang City. Table 1 lists the results.

The minerals are determined by a SX-51 electron microprobe system at the Lithosphere Tectonic Evolution Lab of the Institute of Geology and Geophysics, CAS. Table 2 shows the results.

3.2 Petrological and major elements properties

According to the major and mineral compositions of the samples (Tab. 1, 2 and Fig. 3), the rocks in Daheishan Island are classified as olivine nephelinite (01420H-1, 01420H-3 and 02526H-6) and nepheline basanite (02526H-3 and 02526H-4), and the rock in Cishan is classified as nepheline basanite (01419PW-3).

Nepheline basanite has a porphyritic structure with porphyritic crystals of forsterite, chrysolite, diopside and nepheline. The olivine minerals are altered.

Olivine nephelinite is also porphyritic with microlitic and crypocrystalline structures. The dark minerals are rich. Chrysolite crystals are fresh without altered margin. Pyroxene crystals are diopside and salaite. Feldspar crystals are alkaline loxoclase and anorthoclase.

SiO₂ contents of samples from Daheishan Island are about 40 %, lower than that from Cishan, about 42 % ~ 43 %. For all samples, Na₂O contents are higher than K₂O content, TiO₂ contents are more than 2 %, and Fe₂O₃ contents are higher than FeO contents. This is consistent with the analyzed results of alkaline basalts in Penglai by Chen *et al.*^[5]. It is common for the ultrabasic alkaline rocks that Fe₂O₃ contents are higher than FeO contents. LOI (loss on ignition) is in the range from 0.96 % to 3.4 % except two samples from the roasted layer.

Tab. 1 Major element (wt %) and CIPW normative minerals of samples from Daheishan and Cishan, Penglai, Shandong Province

	01419PW-3	01420H-1	01420H-3	02526H-6	02526H-3	02526H-4	02526H-2	02526H-5
SiO ₂	42.82	39.09	39.3	40.02	40.7	40.08	44.32	41.24
TiO ₂	2.32	2.71	2.79	2.44	2.46	2.53	2.38	2.07
Al ₂ O ₃	12.89	11.74	11.73	11.24	11.77	11.42	10.67	11.48
FeO	5.86	7.57	6.6					
Fe ₂ O ₃	6.67	7.71	8.42	16.15	15.66	15.66	14.76	16.44
MnO	0.16	0.15	0.18	0.23	0.22	0.22	0.21	0.23
CaO	9.64	11.59	11	10.9	11.18	12.05	10.42	9.94
MgO	9.38	9.02	8.88	9.26	8.17	8.29	8.69	7.66
K ₂ O	1.62	2.69	2.62	2.25	1.62	1.40	0.24	0.09
Na ₂ O	4.84	4.5	4.88	4.71	3.27	3.20	1.02	0.69
P ₂ O ₅	1.19	0.96	1.39	1.25	1.32	1.25	1.51	1.50
LOI	2.15	1.78	1.84	0.96	2.40	3.40	5.95	8.27
Tot	99.54	99.51	99.63	99.41	99.22	99.50	100.17	99.60
Quartz							4.1	3.4
Corundum							-	-
Orthoclase	9.9				10.1	8.7	1.5	0.6
Albite	7.9				4.6	1.8	9.3	6.5
Anorthite	8.9	4	2.4	3	13.3	13.3	25.6	31.1
Nepheline	18.6	21.2	23.0	22.2	13.2	14.5	-	-
Leucite		26.8	19.3	13			-	-
Diopside	26.2	39.7	36.2	36.2	29.5	33.6	15.8	10.6
Diopside (Wo)	13.5	20.3	18.5	18.5	15	17.1	8.1	5.4
Diopside (En)	8.3	11.5	10.6	10.4	8.2	9.5	4.6	2.7
Diopside (Fs)	4.4	7.9	7.1	7.3	6.2	7	3.1	2.5
Hypersthene							30.9	35
Hypersthene (En)							18.5	18.4
Hypersthene (Fs)							12.4	16.6
Olivine	17.5	14.1	14.7	16.4	16.9	15.6	-	-
Olivine (Fo)	6.5	6.1	6.3	7.2	7.7	7	-	-
Olivine (Fa)	11	8.0	8.5	9.3	9.2	8.6	-	-
Magnetite	3.5	4.2	4.2	4.2	4.2	4.2	4.1	4.5
Ilmenite	4.5	5.3	5.5	4.8	4.9	5.1	4.9	4.4
Apatite	2.7	2.2	3.1	2.8	3	2.9	3.5	3.6
Name	nepheline basanite	olivine nephelinite	olivine nephelinite	olivine nephelinite	nepheline basanite	nepheline basanite	roasted layer	roasted layer

Tab. 2 Results of electron microprobe analysis for samples from Daheishan Island and Cishan, Penglai, Shandong Province

	PW-3	PW-3	PW-3	H-1	H-1	H-1	H-1	H-3	H-3	H-3	H-3	H-3	H-3	H-3	H-3
SiO ₂	41.11	48.28	49.91	38.46	50.6	47.11	38.83	38.37	38.17	52.70	53.06	52.21	53.92	40.99	41.00
TiO ₂	0.00	2.33	2.00	0.04	1.92	2.83	0.13	0.00	0.02	0.80	0.72	0.99	1.73	0.10	0.01
Al ₂ O ₃	0.09	4.94	4.19	0.00	1.84	3.84	0.01	0.02	0.04	0.39	0.45	0.47	1.56	31.58	31.05
Cr ₂ O ₃	0.04	0.09	0.00	0.00	0.00	0.03	0.00	0.08	0.00	0.09	0.09	0.00	0.00	0.001	0.01
Fe ₂ O ₃		4.50	1.63		3.54	6.57				3.30	2.44	3.41			
MgO	50.75	13.62	13.50	41.27	14.4	12.92	42.12	43.00	42.93	13.23	13.73	13.16	18.53	0.92	0.76
CaO	0.09	23.29	23.28	0.75	23.5	23.27	0.38	0.37	0.31	22.73	22.51	22.06	6.27	0.80	1.31
MnO	0.00	0.20	0.21	0.54	0.02	0.16	0.45	0.37	0.22	0.06	0.20	0.18	0.15	0.00	0.00
FeO	8.57	2.53	5.05	18.46	3.05	1.59	17.66	17.64	17.19	5.29	5.96	5.47	7.66	2.68	2.45
NiO	0.39	0.00	0.00	0.06	0.00	0.03	0.07	0.09	0.08	0.11	0.00	0.06	0.00	0.00	0.00
Na ₂ O	0.03	0.62	0.48	0.03	0.71	0.81	0.00	0.04	0.03	1.17	1.00	1.22	4.88	14.42	14.65
K ₂ O	0.03	0.04	0.03	0.02	0.02	0.18	0.00	0.00	0.01	0.05	0.00	0.08	3.72	7.94	7.82
Total	101.1	100.4	100.2	99.61	99.7	99.32	99.66	99.99	99.00	99.92	100.1	99.31	98.40	99.43	99.13
Si	0.99	1.79	1.85	0.99	1.88	1.77	0.99	0.98	0.98	1.97	1.97	1.96	2.68	2.03	2.04
Ti	0.00	0.06	0.06	0.00	0.05	0.08	0.00	0.00	0.00	0.02	0.02	0.03	0.06	0.00	0.00
Al	0.00	0.22	0.18	0.00	0.08	0.17	0.00	0.00	0.00	0.02	0.02	0.02	0.09	1.84	1.82
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe ³⁺		0.13	0.05		0.10	0.19				0.09	0.07	0.10			
Mg	1.83	0.75	0.75	1.58	0.80	0.73	1.61	1.64	1.65	0.74	0.76	0.74	1.37	0.07	0.06
Ca	0.00	0.92	0.92	0.02	0.94	0.94	0.01	0.01	0.01	0.91	0.90	0.89	0.33	0.04	0.07
Mn	0.000	0.006	0.007	0.012	0.00	0.005	0.010	0.008	0.005	0.002	0.006	0.006	0.006	0.000	0.000
Fe ²⁺	0.17	0.08	0.16	0.40	0.09	0.05	0.38	0.38	0.37	0.16	0.19	0.17	0.32	0.11	0.10
Ni	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.00	0.04	0.03	0.00	0.05	0.06	0.00	0.00	0.00	0.08	0.07	0.09	0.47	1.39	1.41
K	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.24	0.50	0.50
Total	3.01	4.00	4.00	3.01	4.00	4.00	3.00	3.02	3.02	4.00	4.00	4.00	5.57	5.98	6.00
Fo	91.45			80.30			80.99	81.37	81.81						
Fa	8.67			20.15			19.05	18.73	18.38						
Wo		52.84	50.42		51.0	54.61				50.16	48.50	49.27			
Fs		4.82	8.90		5.21	3.20				9.21	10.37	9.84			
En		42.70	40.67		43.7	42.19				40.63	41.14	40.89			
Ab													45.21	71.80	71.41
Or													22.67	26.00	25.07
An													32.12	2.20	3.52
Name	fors- terite	diop- -side	diop- -side	chryso- -lite	diop- -side	diop- -side	chryso- -lite	chryso- -lite	chryso- -lite	diop- -side	salaite	diop- -side	loxo- -clase	anortho clase	anortho clase

On the diagram of total alkaline to SiO₂ (TAS, Fig. 3), three olivine nephelinite samples from Daheishan Island, locate in the foid area. There are nepheline, leucite and only anorthite among the CIPW normative minerals, obviously different from the other samples (Tab. 1).

Although samples 02526H-3and 2526H-4 from Daheishan Island also locate in the region of foid, on account of the high LOI (2.4 % ~ 3.4 %) and the consistence of the CIPW normative minerals with that of nepheline basanite from Cishan (01419PW-3), they are classified as nepheline basanite.

Samples 02526H-2 and 02526H-5 from the roasted layer are merely listed here for reference.

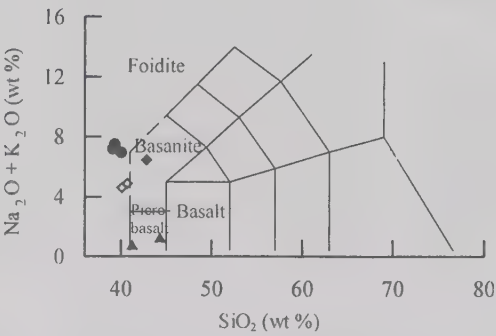


Fig. 3 TAS diagram of the volcanic rocks from Daheishan Island and Cishan, Penglai, Shandong Province
Solid circles, hollow diamonds and triangles respectively are olivine nephelinite, nepheline basanite and roasted layer from Daheishan Island. Solid diamond is nepheline basanite from Cishan.

4 K-Ar age of the volcanic rocks from Daheishan Island

We have selected the K-Ar isotope dilution method to measure the age of the volcanic rocks from Daheishan Island. The samples are crushed to 40 ~ 60 eyes. Olivine crystals are picked out under microscope to the best of our abilities.

Samples 01420H-1 and 01420H-3 (olivine nephelinite) are measured at K-Ar Lab of Chinese Geological Sciences Academy with a MM1200B inert gases mass spectrometer. K contents are analyzed with the XRF method. Sample 02526H-4 (nepheline basanite) is measured at the Laboratory Center of Research Institute of Petroleum Exploration and Development with a MM5400 static vacuum mass spectrometer. The results are shown in Table 3.

Tab. 3 K-Ar isotopic dilution ages of volcanic rocks in Daheishan Island, Penglai, Shandong Province

Sample	K ₂ O (wt %)	Ar _{Measured} weight (g)	⁴⁰ Ar _R (mole/g)	⁴⁰ Ar _R (%)	⁴⁰ Ar/ ⁴⁰ K	Age (Ma)	SD (Ma)
01420H-1	2.12	0.072 3	2.322×10 ⁻¹¹	13.62	0.000 507 9	8.72	0.17
01420H-3	2.37	0.080 0	3.458×10 ⁻¹¹	22.87	0.000 488 8	8.39	0.15
SM-3	1.14		1.600×10 ⁻¹¹	45.88		8.08	0.16
02526H-4	1.24	0.015 4	1.666×10 ⁻¹¹	30.92	0.000 450 5	7.73	0.59

Note: $\lambda = 5.543 \times 10^{-10} \text{ a}^{-1}$, $\lambda_e = 0.581 \times 10^{-10} \text{ a}^{-1}$, $\lambda_\beta = 4.962 \times 10^{-10} \text{ a}^{-1}$, $^{40}\text{K}/\text{K} = 1.167 \times 10^{-4}$. *: Sample SM—3 was measured by Mrs. Chen Wenji at the Institute of Isotopic Geology, Berne University, between 1983 and 1986 (transferred from Liu et al., 1992)^[12].

The K-Ar ages are (8.72 ± 0.17) Ma, (8.39 ± 0.17) Ma and (7.73 ± 0.59) Ma for samples 01420H-1, 01420H-3 and 02526H-4, including the age of (8.08 ± 0.16) Ma by Chen (transferred from Liu et al., 1992)^[12]. However, there is no more description of the rock measured by Chen.

The K-Ar ages of Daheishan Island volcanic rocks reported here are older than those of alkaline basalts (nepheline basanite) from Wuliqiao-Cishan, Penglai (4.03 ~ 5.70 Ma^[14]).

From the measured ages of volcanic rocks in Daheishan Island, it could be concluded that the volcanic rocks erupted in an interval of 0.32 Ma, from 8.72 Ma to 7.73 Ma. Rocks of the former two episodes are olivine nephelinite, and the latest is nepheline basanite.

5 Trace elements of volcanic rocks from Daheishan Island and Cishan

5.1 Analytical method and results

Trace elements of all samples are measured with an Inductively Coupled Plasma Mass Spectrometer (ICP-MS) at the Guangzhou Institute of Geochemistry, CAS. Table 4 lists the results.

Tab. 4 Trace element ($\mu\text{g/g}$) of the Daheishan Island and Cishan volcanic rocks, Penglai, Shandong Province

	P	Sc	Ti	V	Cr	Mn	Co	Ni	Ga	Ge	Rb	Sr
01419PW-3	5240	19.35	14 319.8	179	226.6	1 387.3	50.49	219.9	22.6	1.44	29.77	1 141.1
01420-H1	4 107.3	14.33	17 282.1	200.6	110.3	1 687.8	54.16	102.1	25.46	1.344	30.26	1 662.6
01420H-3	6 090.1	14.71	17 788.8	208	110.1	1608	54.29	108.6	26.09	1.354	29.51	1 565.5
	Y	Zr	Nb	Cs	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd
01419PW-3	28.44	325.2	88.09	0.526	519	63.73	115.2	14.26	56.71	10.72	3.259	8.741
01420-H1	30.88	391.8	122.9	0.563	590.4	88.83	180.6	19.85	77.24	14.04	4.25	11.16
01420H-3	30.53	380.6	123.3	0.534	645.1	87.58	177.3	19.36	75.7	13.79	4.082	10.73
	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta	Pb	Th	U
01419PW-3	1.243	5.985	0.97	2.301	0.273	1.489	0.209	6.803	5.51	4.059	8.807	2.289
01420-H1	1.524	6.89	1.075	2.411	0.271	1.428	0.188	8.62	7.875	4.423	12.45	3.555
01420H-3	1.501	6.886	1.065	2.426	0.267	1.417	0.191	8.262	7.933	6.412	12.75	2.979

Pb elements concentrations of the three samples are between 4.1×10^{-6} and 6.4×10^{-6} . Since Pb concentrations of some continental and oceanic island basalts without contaminating by crustal materials are commonly in the range of 1×10^{-6} and 3×10^{-6} , there is crustal Pb element contamination in volcanic rocks in this area. This is consistent with Chen and Peng's^[4] cognition.

5.2 Rare-earth elements

It is obvious from the distribution patterns of rare-earth elements (Fig. 4) that volcanic rocks from Daheishan Island and Cishan are rich in light REEs.

5.3 Trace element normalized model by primordial mantle

All samples are similar to ocean island basalts^[13] in the trace element normalized model by primordial mantle (Fig. 5). Data of samples from Daheishan Island and Cishan are rich in both high field strength elements (HFSE) such as Nb and Ta, and strong incompatible elements such as Cs, Rb, Ba, Tu and U. The normalized values of elements from La to Lu, decrease with the descending of the incompatibilities. But the HFSEs and strong incompatible elements of volcanic rocks from Daheishan Island and Cishan are higher than those of OIBs.

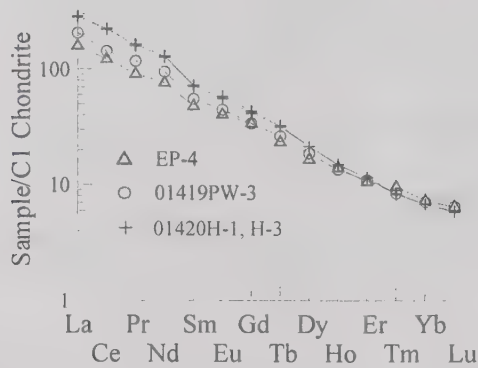


Fig. 4 REE distribution patterns of samples from Daheishan Island and Cishan, Penglai, Shandong Province

The crosses are Daheishan Island samples. Solid circle is Cishan sample. Triangle is sample EP-4 from Wuliqiao-Cishan measured by Zhi (1990)^[9].

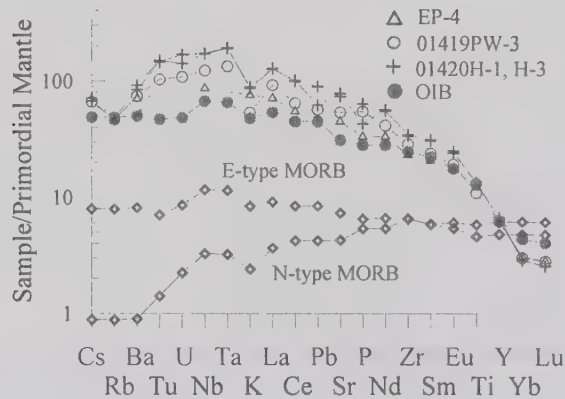


Fig. 5 Trace element normalized model by primordial mantle of volcanic rocks in Daheishan Island and Cishan, Penglai, Shandong Province

Data of primordial mantle, MORB and OIB are from Sun and McDonough (1989)^[13]. Data of EP-4 is from Wuliqiao-Cishan, Penglai by Zhi (1990)^[9].

Because elements of Nb and Ta are strongly depleted in crust and island-arc volcanic rocks, it could be deduced that the volcanic rocks from Daheishan Island and Cishan have been originated from the deep mantle reservoirs beneath the continent.

Strong mobile elements such as K and Rb are depleted in the volcanic rocks from Daheishan Island (Fig. 5).

6 Sr, Nd and Pb isotopic properties

6.1 Analytical method and results

Sr, Nd and Pb isotopic compositions for volcanic rocks are determined with a Finnigan-MAT261 mass spectrometer at the Geological Institute of Chinese Geological Sciences Academy. The results are listed in Table 5.

No age correction is applied because of the very young K-Ar ages of the volcanic rocks. The measured Sr, Nd and Pb isotopic compositions are used in this paper.

Sm-Nd isotopic ratios of olivine nephelinite from Daheishan Island ($^{147}\text{Sm} / ^{144}\text{Nd} = 0.110\ 3 \sim 0.114\ 0$, $^{143}\text{Nd} / ^{144}\text{Nd} = 0.512\ 910 \sim 0.513\ 074$) are close to those from Cishan ($^{147}\text{Sm} / ^{144}\text{Nd} = 0.118\ 6$, $^{143}\text{Nd} / ^{144}\text{Nd} = 0.513\ 014$). $^{143}\text{Nd} / ^{144}\text{Nd}$ value of volcanic rock from Cishan is lower than the results measured by Zhi *et al.* (1994, $^{143}\text{Nd} / ^{144}\text{Nd} = 0.512\ 845 \sim 0.512\ 865$)^[10].

Rb-Sr isotopic ratios of samples from Daheishan Island are lower than those from Cishan. $^{87}\text{Rb} / ^{86}\text{Sr} = 0.053\ 67 \sim 0.049\ 66$ and $^{87}\text{Sr} / ^{86}\text{Sr} = 0.703\ 427 \sim 0.703\ 482$ for Daheishan Island samples, and $^{87}\text{Rb} / ^{86}\text{Sr} = 0.077\ 10$ and $^{87}\text{Sr} / ^{86}\text{Sr} = 0.703\ 895$ for Cishan sample. Rb-Sr isotopic ratios of Cishan sample are consistent with those measured by Chen *et al.* (1985, $^{87}\text{Sr} / ^{86}\text{Sr} = 0.703\ 87 \sim 0.704\ 32$), but lower than those analyzed by Zhi *et al.* (1994, $^{87}\text{Sr} / ^{86}\text{Sr} = 0.703\ 93 \sim 0.704\ 48$)^[10].

All Pb isotopic ratios of samples from Daheishan Island ($^{206}\text{Pb} / ^{204}\text{Pb} = 18.028\ 9 \sim 17.972\ 8$, $^{207}\text{Pb} / ^{204}\text{Pb} = 15.435\ 8 \sim 15.402\ 2$ and $^{208}\text{Pb} / ^{204}\text{Pb} = 38.087\ 6 \sim 37.997\ 5$) are lower than those from Cishan ($^{206}\text{Pb} / ^{204}\text{Pb} = 18.240\ 1$, $^{207}\text{Pb} / ^{204}\text{Pb} = 15.564\ 5$ and $^{208}\text{Pb} / ^{204}\text{Pb} = 38.535$). Measured results of Cishan sample are in agreement with those measured by Chen *et al.* (1985, $^{206}\text{Pb} / ^{204}\text{Pb} = 18.179 \sim 18.384$, $^{207}\text{Pb} / ^{204}\text{Pb} = 15.502 \sim 15.555$ and $^{208}\text{Pb} / ^{204}\text{Pb} = 38.300 \sim 38.518$)^[4].

6.2 ϵ_{Nd} valuesd

The $\epsilon_{\text{Nd}}(0)$ and $\epsilon_{\text{Nd}}(t)$ values of Daheishan Island and Cishan samples are all higher than 0 (Tab. 5), indicating the magmas of volcanic rocks both in Daheishan Island and Cishan derived from

Tab. 5 Sr-Nd-Pb isotopic compositions of the volcanic rocks in Daheishan Island and Cishan, Penglai, Shandong Province

	01420H-1	01420H-3	01420PW-3
Rb ($\times 10^{-6}$)	29.44	27.61	29.32
Sr ($\times 10^{-6}$)	1 588	1 610	1 101
$^{87}\text{Rb} / ^{86}\text{Sr}$	0.053 67	0.049 66	0.077 10
$^{87}\text{Sr} / ^{86}\text{Sr} (\pm 2 \sigma)$	$0.703\ 427 \pm 12$	$0.703\ 482 \pm 10$	$0.703\ 895 \pm 13$
Sm ($\times 10^{-6}$)	13.02	13.14	10.30
Nd ($\times 10^{-6}$)	71.49	69.75	52.51
$^{147}\text{Sm} / ^{144}\text{Nd}$	0.110 2	0.114 0	0.118 6
$^{143}\text{Nd} / ^{144}\text{Nd} (\pm 2 \sigma)$	$0.512\ 910 \pm 9$	$0.513\ 074 \pm 12$	$0.513\ 014 \pm 9$
$\epsilon_{\text{Nd}}(0)$	5.31	8.51	7.33
$\epsilon_{\text{Nd}}(t)$	5.40	8.59	7.39
$^{206}\text{Pb} / ^{204}\text{Pb} (\pm 2 \sigma)$	$18.028\ 9 \pm 43$	$17.972\ 8 \pm 16$	$18.240\ 1 \pm 43$
$^{207}\text{Pb} / ^{204}\text{Pb} (\pm 2 \sigma)$	$15.435\ 8 \pm 22$	$15.402\ 2 \pm 14$	$15.564\ 5 \pm 37$
$^{208}\text{Pb} / ^{204}\text{Pb} (\pm 2 \sigma)$	$38.087\ 6 \pm 54$	$37.997\ 5 \pm 33$	38.535 ± 9

sources with a greater Sm / Nd than CHUR, *i.e.* depleted mantle source regions^[14].

6.3 Sr, Nd and Pb isotopic properties

By comparing with Sr, Nd and Pb isotopic compositions summarized by Rollinson^[14], all isotopic ratios of Daheishan Island except $^{206}\text{Pb} / ^{204}\text{Pb}$ are close to those of E-type MORB ($^{87}\text{Sr} / ^{86}\text{Sr} = 0.70280 \sim 0.70334$, $^{143}\text{Nd} / ^{144}\text{Nd} = 0.51299 \sim 0.5130$, $^{206}\text{Pb} / ^{204}\text{Pb} = 18.50 \sim 19.69$, $^{207}\text{Pb} / ^{204}\text{Pb} = 15.50 \sim 15.60$, $^{208}\text{Pb} / ^{204}\text{Pb} = 38.0 \sim 39.3$). The dominant mantle components of E-MORB are DM and PREMA. Except $^{206}\text{Pb} / ^{204}\text{Pb}$, all isotopic ratios are also in the region of oceanic basalts in Hawaii ($^{87}\text{Sr} / ^{86}\text{Sr} = 0.703170 \sim 0.70412$, $^{143}\text{Nd} / ^{144}\text{Nd} = 0.512698 \sim 0.513060$, $^{206}\text{Pb} / ^{204}\text{Pb} = 17.83 \sim 18.20$, $^{207}\text{Pb} / ^{204}\text{Pb} = 15.44 \sim 15.48$, $^{208}\text{Pb} / ^{204}\text{Pb} = 37.69 \sim 37.86$).

Isotopic ratios of Cishan basanite are consistent with those of oceanic basalts in Kerguelen ($^{87}\text{Sr} / ^{86}\text{Sr} = 0.703880 \sim 0.705980$, $^{143}\text{Nd} / ^{144}\text{Nd} = 0.512498 \sim 0.513062$, $^{206}\text{Pb} / ^{204}\text{Pb} = 17.99 \sim 18.31$, $^{207}\text{Pb} / ^{204}\text{Pb} = 15.48 \sim 15.59$, $^{208}\text{Pb} / ^{204}\text{Pb} = 38.29 \sim 38.88$). DM I (Dupal type) is the dominant mantle component for Kerguelen OIB.

Therefore Sr, Nd and Pb isotopic compositions for volcanic rocks in Daheishan Island and Cishan are close to or consistent with E-MORB or OIBs. This means there is no contamination of crustal materials for the isotopic compositions. Although the crustal Pb contamination is obvious, the Pb isotopic compositions of these samples do not decrease significantly.

On the isotope correlation diagrams (omitted here) of $^{143}\text{Nd} / ^{144}\text{Nd}$ vs $^{87}\text{Sr} / ^{86}\text{Sr}$, $^{87}\text{Sr} / ^{86}\text{Sr}$ vs $^{206}\text{Pb} / ^{204}\text{Pb}$ and $^{143}\text{Nd} / ^{144}\text{Nd}$ vs $^{206}\text{Pb} / ^{204}\text{Pb}$, it is clear that all samples are close to or even in the region of PREMA. This strongly implies that the PREMA component plays an important role in the volcanic rocks in Daheishan Island and Cishan.

On the basis of above analyses, it could be deduced that the mantle dominant components for the Daheishan Island and Cishan volcanic rocks are DM, PREMA and perhaps DM I (Dupal type). Our results are consistent with previous cognitions. For example, Zhou *et al.*^[11] suggested the Cenozoic basalts in the eastern China have mantle resources of DM I (Dupal type). As for the Cenozoic basalts around the Bohai Sea, PREMA is very important^[15].

7 Conclusions

From the analyses of major elements, K-Ar age, trace elements, Sr, Nd and Pb isotopic systems for the volcanic rocks in Daheishan Island and Cishan, it could be concluded that:

(1) the volcanic rocks in Daheishan Island (olivine nephelinite and nepheline basanite) erupted in an interval of 0.32 Ma, from 8.72 Ma, 8.39 Ma, 8.08 Ma to 7.73 Ma.

(2) all samples are similar to ocean island basalts in the trace element normalized model by primordial mantle, rich in both HFSEs such as Nb and Ta, and strong incompatible elements such as Cs, Rb, Ba, Th and U, suggesting that the volcanic rocks from Daheishan Island and Cishan are originated from the deep mantle reservoirs beneath the continent.

(3) the positive $\epsilon_{\text{Nd}}(0)$ and $\epsilon_{\text{Nd}}(t)$ values indicate the magmas of volcanic rocks both in Daheishan Island and Cishan derived from depleted mantle source regions.

(4) Sr, Nd and Pb isotopic compositions for volcanic rocks in Daheishan Island and Cishan are close or consistent with E-MORB or OIBs, meaning there is no contamination of crustal materials for the isotopic compositions.

(5) the mantle dominant components for the Daheishan Island and Cishan volcanic rocks are DM,

PREMA and perhaps DM I (Dupal type). The PREMA component plays an important role.

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Vegetation of Mangroves: Spatial and Temporal Pattern of its Dominant Populations in Futian National Nature Reserve

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Abstract The community characteristics of mangroves in the Futian Nature Reserve, Shenzhen, China are given based on surveying of 33 quadrats in 4 transects which stretch from the higher tidal zone to the lower tidal zone. The results show that there are 6 community types in this area: *Kandelia candel* association, *Avicennia marina* association, *Aegiceras corniculatum* association, *Kandelia candel* + *Aegiceras corniculatum* association, *Aegiceras corniculatum* + *Kandelia candel* association and *Acanthus ilicifolius* association. *Kandelia candel*, *Aegiceras corniculatum* and *Avicennia marina* dominate the typical quadrats. *Kandelia candel* can be seen at almost all quadrats, *Aegiceras corniculatum* distributes mostly toward the estuary and the higher tidal zone, *Avicennia marina* distributes mostly toward the bay and the lower tidal zone, *Bruguiera gymnorhiza* occasionally occurs toward the Estuary with one or several individuals, *Acanthus ilicifolius* was common toward the higher tidal zone, as an accompanying species, *Derris trifoliata* was common in many mature quadrats. Totally, 6 species of mangrove plants and 3 species of semi-mangrove plants appear in this research area. From the higher tidal zone to the lower tidal zone, the average diameter and basal area of mangrove trees increase gradually. According to the results, the *Avicennia marina* dominates in average diameter and basal area, and the *Aegiceras corniculatum* trees are on the contrary. From the transect 1 to the transect 4, the importance value of *Avicennia marina*, *Bruguiera gymnorhiza* and *Kandelia candel* decreases, and *Aegiceras corniculatum* increases. In this area, the *Kandelia candel* population and *Aegiceras corniculatum* population are developing populations with many seedlings and saplings, but the *Avicennia marina* population is in a mature stage with few seedlings and not so many total individuals. According to this research, we suppose that *Aegiceras corniculatum* should be developed toward the estuary and the *Avicennia marina* association should be protected.

Keywords Vegetation analysis, *Kandelia candel*, *Avicennia marina*, *Aegiceras corniculatum*, Community, Population structure, Shenzhen

1 Introduction

Mangroves are the dominant intertidal ecosystems throughout the tropical and subtropical regions of the world and enter the subtropics as far north as Japan (32° N) and as far south as Victoria, Australia (38° 54.8' S)^[1-2]. The climate and landform characteristics of a coastal region together with local ecological processes control the basic properties of mangrove wetlands^[3, 4]. Lower scale factors

such as microtopography and tidal hydrology can influence the zonation of mangroves from shoreline to the farther inland locations forming ecological types of mangrove wetlands^[11, 51]. Twilley (1995, 1997) suggested that a gradient in the geophysical processes of a coastal region together with local ecological factors will determine the diverse patterns of energy flow and biogeochemistry of mangrove wetlands^[4, 6]. Since mangroves are considered naturally stressed ecosystems^[17], their structural complexity is shaped by many cyclic events, so they usually reach maturity in 20 ~ 30 a^[8] and can also be considered as systems with multiple equilibrium states^[9, 10]. Natural disturbances at a smaller spatial scale can also influence mangrove species zonation and succession^[8, 11, 12]. Sometimes they can also shape landscape patterns of vegetation distribution at larger spatial and temporal scales^[13, 14].

The restoration rate of mangroves from a disturbance depends on the particular species that survive the disturbance^[15]. Thus initial conditions of mangroves structure and rates of sapling recruitment are important for mangroves development^[16]. Differences in mortality and growth rates in several areas across the landscape in mangrove forests will also have a strong influence on the spatial distribution of mangrove species since competition for resources among mangrove species is expected to affect regeneration dynamics^[17-19].

It is assumed that mangroves are net exporters of organic matter that provide detritus for the higher trophic levels^[2, 20-23]. Here, the mangrove plants not only stabilize the estuary ecosystem, keep the species diversity, but also provide a habitat for many birds, insects, fishes, invertebrates and microbes in this area and support a complex food web. Mangroves are also important to the subsistence economics all the world, providing firewood, building materials, and other wood products, as well as ecosystem services such as water quality maintenance, storm wave protection, fish habitat, and ecotourism activities^[23-26]. With increasing population pressure, these forests are now extensively exploited^[27].

In this paper, based on surveying of 33 quadrats in 4 transects which stretch from the higher tidal zone to the lower tidal zone the mangroves in Futian Nature Reserve have been studied. By comparing the vegetations of mangroves and the spatial and temporal pattern of the dominant mangrove populations, we try to provide data for management, conservation and restoration of mangroves and other biodiversity in this region.

2 Study site and methods

2.1 Study area

The study area is located in the Futian Mangrove Nature Reserve (22° 32' N, 114° 03' E), about 8 km south of Shenzhen, Southern China. The wetland of Shenzhen River, its estuary, and Shenzhen Bay is an internationally important wetland. The Futian National Nature Reserve is one of its core parts as well as the Mai Po Nature Reserve of Hong Kong which has recently been included in the List of Wetlands of International Importance under the RAMSAR Convention (Convention on Wetlands of International Importance Especially as Habitat for Water Birds). This area and its surrounding environment provide a habitat for birds to live and get food in. There are 189 species of birds, including waterfowl, migratory birds and raptors in this area^[28, 29]. Because more and more coastal bird habitats have been destroyed, some species are in crisis throughout the world, here the mangroves has become an important wetland for migratory birds to live and get food in. It is located in southern subtropical evergreen broadleaved forest zone and stretches 11 km from the Shenzhen Bay to Shenzhen River, and covers an area of 304 ha. And the adjacent land is a mosaic of disturbed pond and cultivated land. The

predominant soil type in mangroves is muddy earth.

The climate of this area is a hot, oceanic monsoon one. The mean annual temperature is 22℃ and 0.2℃ (minimum) and 38.7℃ (maximum), and the mean annual precipitation is 1 927 mm, which occurs principally during May to September, and the mean annual relatively humidity 79 %. The mean monthly radiation is 450 J • m, with the highest radiation in August (590 J / m²) and the lowest in February (322 J / m²). The mean duration of light is 6.1 h / d, with the minimum and maximum hours of radiation occurring in February (4.2 h / d) and August (7.8 h / d) respectively. The mangrove forest is inundated by incoming tide twice a day and the spring tidal range is about 2.8 m.

The soil ranges from sandy clays in the Bay to silty clays in the estuary, the clays were deep and structureless, and the salinity of surface clays (14.48) and pH value (5.30) were lower than that of the deeper layer clays (18.21 ~ 19.28 and 6.58 ~ 7.14) (Tab. 1).

Tab. 1 Soil physicochemical properties of mangroves stand in Futian Nature Reserve^[30]

Depth (cm)	pH Value	Salinit	Volume Weight (g/cm ³)	Concentration of elements (% dw)			
				K	Na	Ca	Mg
0~30	5.30	14.48	0.460	1.25	0.70	0.11	0.94
30~60	6.58	18.21	0.618	1.17	0.68	0.11	0.86
60~90	7.14	19.28	0.640	1.05	0.55	0.10	0.70

2.2 Measurements

Ground survey has been undertaken from February to March and four zonary transects (T1, T2, T3, T4) which are 10 m wide and perpendicular to the coastline (from the higher tidal zone to the lower tidal zone) established. Transect T1 is near the Shenzhen Bay end, Transect T4 near the Shenzhen Estuary end. Transect T3 across the widest mangroves swamp which is about 285 m in width (Fig. 1). Along each transect, 10 m by 10 m quadrat per 20 m is delimited and exhaustively sampled. In each

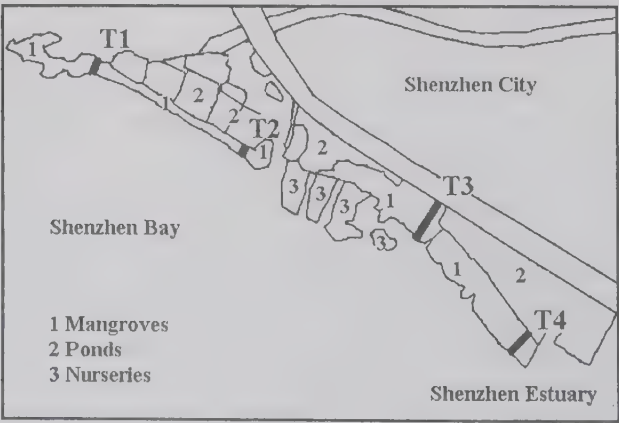


Fig. 1 Location of 4 Transects in Futian Mangrove Nature Reserve

quadrat along the transects, the quadrat method is used to estimate structural parameters, height, diameter at breast height (DBH; the minimum sampling diameter is 2.5 cm), density, dominance, frequency, and the importance value (IV) for all tree species is recorded^[31, 32]. The abundance is the numbers of the species in the same quadrat or a transect, frequency is the probability of finding the species in the same quadrat or a transect, dominance is the total basal area per species, and basal area is the cross-sectional area of the tree at a point 1.3 m above ground. Then the three values of relative abundance (RA), relative frequency (RF) and relative dominance (RD) are summed to obtain for each species its importance value (IV)^[33]. Trees, which branch below the breast height, are treated as several stems, and the parameter of each branch is recorded. For saplings (DBH < 2.5 cm) or shrubs or seedlings, only the individual numbers are recorded.

3 Results

3.1 Species distribution

According to the survey on this area, there are 6 mangrove species, 4 semi-mangrove species and 1 accompanying species in the Futian Nature Reserve. Mangrove species includes *Kandelia candel* (L.) Dance (Rhizophoraceae), *Bruguiera gymnorhiza* (L.) Savigny (Rhizophoraceae), *Aegiceras corniculatum* (L.) Blanco. (Mysinaceae), *Avicennia marina* (Forsk.) Vierh (Verbenaceae), *Acanthus ilicifolius* Linn. (Acanthaceae) and *Excoecaria agallocha* Linn. (Euphorbiaceae). Semi-mangrove species are *Acrostichum aureum* Linn., *Thespesia populnea* (L.) Engl. and *Pluchea indica* (L.) Less., and *Derris trifoliata* (accompanying species) is a common liana species in mature community.

The species distribution along transects is shown in Figure 2. All the 4 transects have a clear zonation pattern. Five mangrove species could be seen in all the 4 transects, and the accompanying species *Derris trifoliata* has been surveyed except in T4. *Kandelia candel* dominates the quadrats toward the higher tidal zone, where there are some *Aegiceras corniculatum*, *Acanthus ilicifolius*, *Derris trifoliata*, and a few *Bruguiera gymnorhiza*. In the quadrats of the middle tidal zone, 5 mangrove species are found frequently. And in the lower tidal zone, only *Avicennia marina*, *Kandelia candel* and *Aegiceras corniculatum* can be found. *Acanthus ilicifolius* is a lower shrub and mainly grows in the mud bank of creek along the seashore. *Acrostichum aureum* has been only seen toward the higher tidal zone, *Thespesia populnea* and *Pluchea indica* which have been recorded in previous researches^[34] are not found on the 4 transects in this survey.

From the estuary to the bay along the seashore we could also find a different distribution pattern, *Aegiceras corniculatum* mainly distributes in the estuary, and sometimes formes a pure association. But at the bay, we almost cannot find it. In contrast, in T4, T3, there are only a few individuals of *Avicennia marina*. The *Avicennia marina* becomes more and more common from the estuary to the bay, then in T1, it forms pure association, and its relative density reaches 100 %. *Kandelia candel* is common from the estuary to the bay, but *Bruguiera gymnorhiza* is rare throughout this area. *Acanthus ilicifolius* is common toward the higher tidal zone at the 4 transects, but *Derris trifoliata* could not be found in T1.

3.2 Density of mangrove plants

Tree density (individuals per ha) varies in different communities. It is lowest in *Avicennia marina* association (only 3 200~10 000/hm²) in the quadrat 5 to the quadrat 6 in transect 1. It is intermediate condition (6 400~ 20 000/hm²) in *Kandelia candel* association in all transects. It is nearly 30 000/hm² in *Aegiceras corniculatum* association in the quadrat 6 in T4. The DBH of *Acanthus ilicifolius* is smaller

than 2 cm, but its density can reach 200 000/hm².

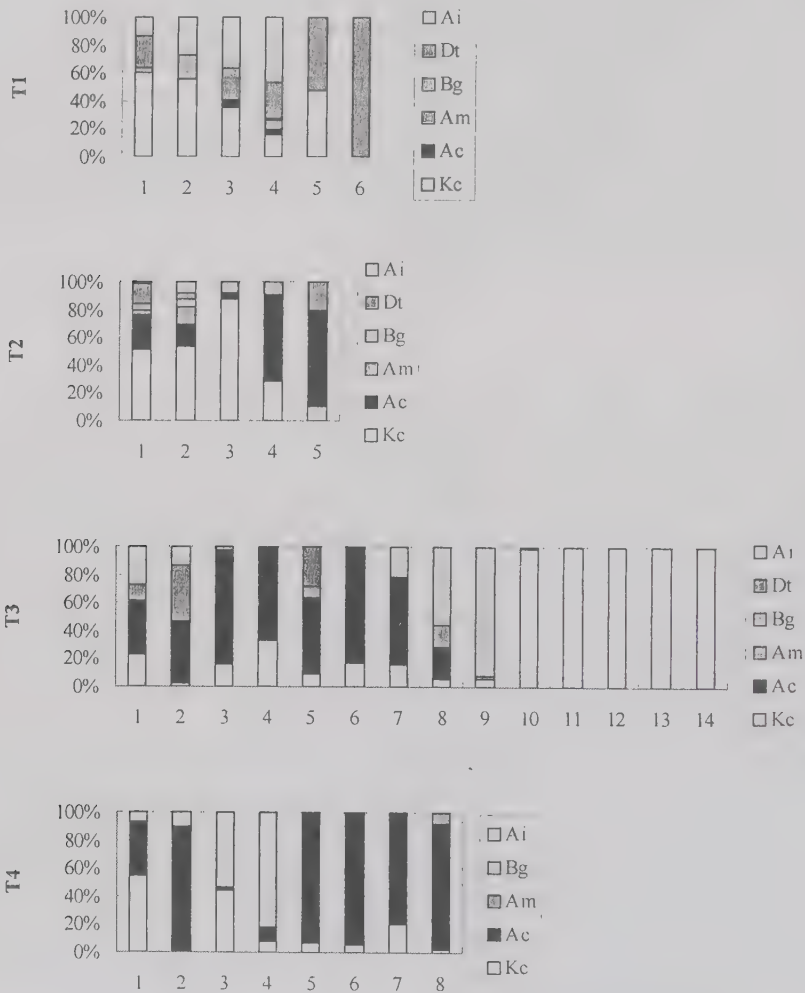


Fig. 2 Distribution of mangrove plants along transects (Percent of density)

Kc: *Kandelia candel*; Ac: *Aegiceras corniculatum*; Am: *Avicennia marina*; Bg: *Bruguiera gymnorrhiza*; Dt: *Derris trifoliata*; Ai: *Acanthus ilicifolius*

3.3 Mean stand diameter and total basal area

As indicated in Figure 3, the mDBH of all transects increases in the mass from the higher tidal zone to the lower tidal zone. In T1, the mDBH decreases smoothly from quadrat 1 to quadrat 3, then increases rapidly from 4.83 cm in quadrat 3 to the peak 13.81 cm in quadrat 7. It is due to the big *Avicennia marina* trees. In T2, the mDBH of stand changes smoothly between 4.49 cm to 6.42 cm, with a little lower in quadrat 1 (4.49 cm) and quadrat 4 (5.26 cm) due to too many *Aegiceras corniculatum* trees. The mDBH of stand in T3 increases in the mass from the higher tidal zone to the lower tidal zone, and it reaches a second peak (5.50 cm) in quadrat 5 for a narrow zone which stretches from T1 and makes up

of *Avicennia marina* mainly, followed by two lower mDBHs (3.67 cm and 3.38 cm) due to many small *Kandelia candel* and *Aegiceras corniculatum* trees. The mDBH of stand in T4 is almost the same (4.92) except in quadrat 1 (5.78) where the stand is composed of *Kandelia candel* mainly.

As indicated in Figure 3, the total basal area in different quadrats varies greatly, for its value depends on the dominant species remarkably and the number of individuals in a quadrat. For example, the total basal area of quadrat 6 in T1 reaches the peak 1 213.80 cm² due to mature *Avicennia marina* tree and is bigger than the others. Sometimes the total basal diameter of *Aegiceras corniculatum* and *Kandelia candel* associations is small due to few trees in the quadrat.

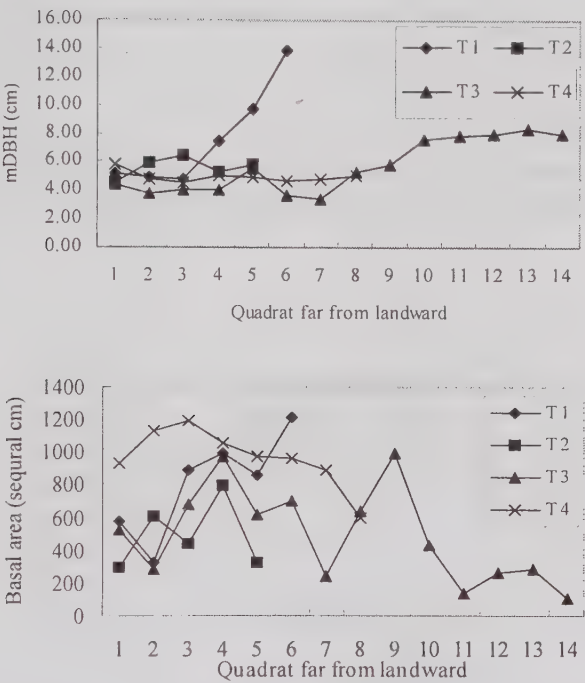


Fig. 3 Change of mean DBH and basal area (cm²) from the higher tidal zone to the lower tidal zone in 4 transects

3.4 Importance-value of trees in transect

The importance value is an all-around parameter to consider the importance of a species in a community^[32, 35]. Here we use it to consider the importance of four species in different transects. As indicated in Figure 4, the importance value (IV) of *Kandelia candel* is the biggest (T1: 159.00; T2: 132.55; T3: 163.30) except in transect 4. The IV of *Avicennia marina* is inferior to *Kandelia candel* in transect 1, and it becomes less and less from the Shenzhen Bay to the Shenzhen estuary. But *Aegiceras corniculatum* behaves the contrary way, it has a smaller IV in transect 1, then its IV becomes higher and higher, to the biggest one (176.1) in transect 4 located in the Shenzhen estuary. The IV of *Avicennia marina* is evidently in negative correlation with that of *Aegiceras corniculatum*, and the correlation formula is: $y = -1.6383x + 180.38$, $r = -0.9627$. In all the 4 transects, *Bruguiera gymnorrhiza* has the smallest IV.

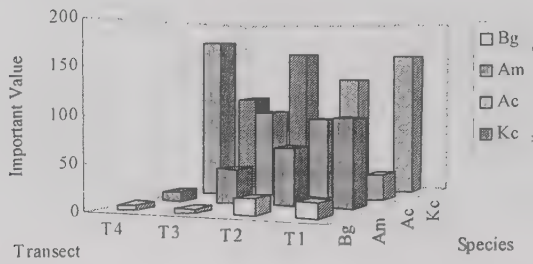


Fig. 4 Importance Value (IV) of 4 tree mangrove species in different transects
Kc: *Kandelia candel*; Ac: *Aegiceras corniculatum*; Am: *Avicennia marina*; Bg: *Bruguiera gymnorrhiza*

3.5 Population structure

Considering 3 dominant populations in this area (Fig. 5), we can find that *Avicennia marina* population has few seedlings and not so many total individuals, and we think it is in a mature stage.

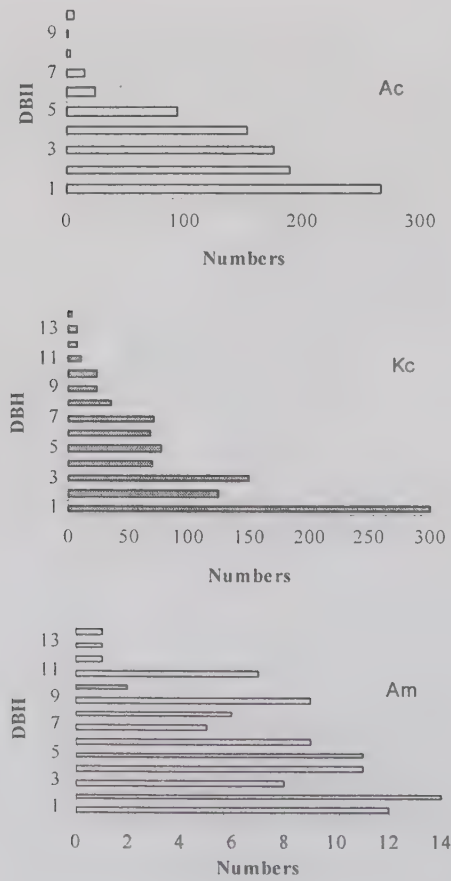


Fig. 5 The DBH structure of *Avicennia marina* (Am), *Kandelia candel* (Kc) and *Aegiceras corniculatum* (Ac) populations

Kandelia candel population and *Aegiceras corniculatum* population are developing populations with many seedlings and saplings, Here the *Kandelia candel* population is a typical developing population. As plants grow older, fewer and fewer trees could be found. *Aegiceras corniculatum* is a shrub-like plant, so the DBH of most individuals is below 5 cm.

3.6 Survival curve of three main mangrove trees

Consider the survival curve of 3 dominant populations in this area (Fig. 6). The results show that the percentage of adults decreases with the mean DBH, the survival curve of *Kandelia candel* population and *Aegiceras corniculatum* population fits the Deevey type III with a pattern of high juvenile and low adult mortality, but that of *Avicennia marina* population fits the Deevey type II with a constant death risk throughout^[36].

3.7 Vegetation of mangroves

After thorough survey and analysis, the mangroves in the Futian Nature Reserve can be divided into six community types: *Kandelia candel* association, *Avicennia marina* association, *Aegiceras corniculatum* association, *Kandelia candel* + *Aegiceras corniculatum* association, *Aegiceras corniculatum* + *Kandelia candel* association and *Acanthus ilicifolius* association.

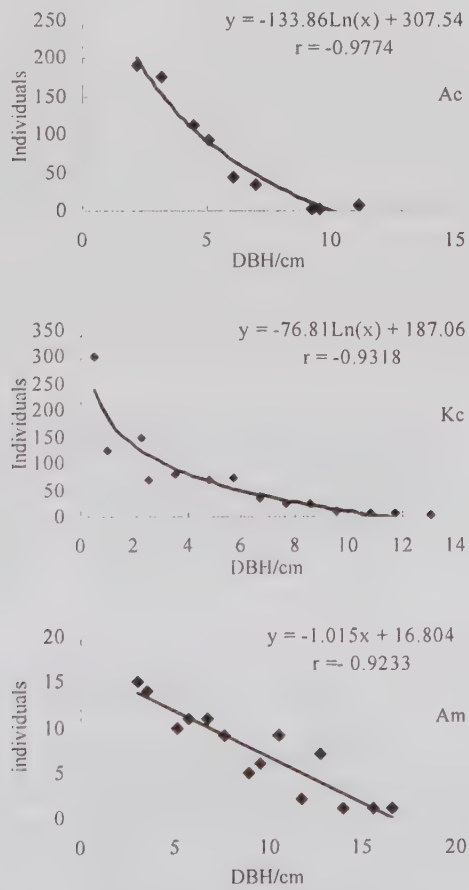


Fig. 6 The survival curve of *Aegiceras corniculatum* (Ac), *Kandelia candel* (Kc) and *Avicennia marina* (Am) population

(1) *Kandelia candel* association: *Kandelia candel* association exists in all the four transects. Sampling one typical quadrat to represent this association from each transect, the statistical result is shown in Table 2. This association is dominated by *Kandelia candel* absolutely with high importance value ($IV = 198.7$), occasionally with several *Aegiceras corniculatum* and *Avicennia marina* or *Bruguiera gymnorrhiza* in the quadrat. Saplings and seedlings of *Kandelia candel* are abundant. In addition there are many individuals of *Acanthus ilicifolius* in the shrub layer. Coverage of this association ranges from 90 % to 100 %. In some quadrats, *Derris trifoliata* (height 4.5 ~ 5.0 m) accompanies.

Tab. 2 Results of quadrats analysis for *Kandelia candel* association in Futian Nature Reserve (5 m×5 m, × 4 quadrats)

Spp.	No.	Occ.	DBH (cm ²)	RA (%)	RF (%)	RD (%)	IV	Rank
Kc	110(47)*	4	28 373	79.7	36.4	82.6	198.7	1
Ac	12(5)	4	1 968	8.7	36.4	5.7	50.8	2
Am	13	1	3 702	9.4	9.0	10.8	29.2	3
Bg	3	2	302	2.2	18.2	0.9	21.3	4
Ai	596	3						

*Brackets indicate seedling numbers. The follow tables were the same.

(2) *Avicennia marina* association: *Avicennia marina* association grows well toward the seaside of transect 1 and transect 2, and also appears in the central section of transect 3. Surveying four quadrats, the results are shown in Table 3. Canopy of this association is dominated by trees of *Avicennia marina*, accompanied by a few trees of *Kandelia candel* and *Aegiceras corniculatum*. Under the canopy there are many seedlings of *Aegiceras corniculatum* and *Kandelia candel*, but no seedlings of *Avicennia marina*. As viewed from the succession of the community, the *Avicennia marina* association may be replaced by *Kandelia candel* association or *Kandelia candel* + *Aegiceras corniculatum* association sometime later. The coverage of the community is over 80 % and the tree is only 3.5 ~ 4.5 m in height.

Tab. 3 Results of quadrats analysis for *Avicennia marina* association in the Futian Nature Reserve (5 m×5 m, × 4 quadrats)

Spp.	No.	Occ.	DBH (cm ²)	RA (%)	RF (%)	RD (%)	IV	Rank
Am	49	4	32 583	80.3	44.5	96.0	220.8	1
Kc	7(12)	3	970	11.5	33.3	2.9	47.7	2
Ac	5(39)	2	377	8.2	22.2	1.1	31.5	3
Ai	72	1						

(3) *Aegiceras corniculatum* association: *Aegiceras corniculatum* association can only be seen in the transects 3 and 4. Sampling four quadrats, the results show that the association is dominated by *Aegiceras corniculatum* with more individuals, and sub-dominated by *Kandelia candel*. In this association we can hardly find *Avicennia marina* and *Bruguiera gymnorrhiza*. The association regenerates very well for the *Aegiceras corniculatum* and *Kandelia candel* populations appearing in a pyramidal age structure. In addition, a few of *Derris trifoliata* and *Acanthus ilicifolius* appear in the quadrat toward land. The association height is 2.5 ~ 4.5 m (Tab. 4).

Tab. 4 Results of quadrat analysis for *Aegiceras corniculatum* association in the Futian Nature Reserve (5 m×5 m, × 4 quadrats)

Spp.	No.	Occ.	DBH (cm ²)	RA (%)	RF (%)	RD (%)	IV	Rank
Ac	142(28)	4	40 447	88.2	50	84.2	222.4	1
Kc	19(2)	4	7 585	11.8	50	15.8	77.6	2
Ai	37	2						
Dt	36	1						

(4) *Kandelia candel* +*Aegiceras corniculatum* association: This association is distributed in the transects 2, 3 and 4. The results show that the relative dominance of *Kandelia candel* is almost 3 times larger than that of *Aegiceras corniculatum* in this association, but relative abundance of the two species is almost the same. According to the results of investigation, there are so many saplings and seedlings in the forest that the association regenerates well. *Bruguiera gymnorrhiza* could be found occasionally. We can also find some *Acanthus ilicifolius* and *Derris trifoliata* in this association. Canopy of this community is so prosperous that the coverage is up to nearly 100 % (Tab. 5).

Tab. 5 Results of quadrats analysis for *Kandelia candel* + *Aegiceras corniculatum* association (5 m×5 m, × 4 quadrats)

Spp.	No.	Occ.	DBH (cm ²)	RA (%)	RF (%)	RD (%)	IV	Rank
Kc	53(43)	4	15 490	48.6	44.5	75.0	168.1	1
Ac	55(76)	4	4 808	50.5	44.5	23.3	118.3	2
Bg	1(2)	1	345	0.9	11.0	1.7	13.6	3
Ai	50	2						
Dt	24	2						

(5) *Aegiceras corniculatum* + *Kandelia candel* association: The association distributes in the transects 2, 3 and 4. The results are shown in Table 6. This community is similar to the former one. In this association, there are so many trees of *Aegiceras corniculatum* that its relative abundance (RA) is 3 times that of *Kandelia candel*, and the importance value of *Aegiceras corniculatum* is as high as 161.1. There are also a large number of individuals of *Acanthus ilicifolius* and a few of *Avicennia marina* and *Bruguiera gymnorrhiza*.

Tab. 6 Results of quadrats analysis for *Aegiceras corniculatum* + *Kandelia candel* association (5 m×5 m, × 4 quadrats)

Spp.	No.	Occ.	DBH (cm ²)	RA (%)	RF (%)	RD (%)	IV	Rank
Ac	138(52)	4	20 147	72.6	36.4	52.1	161.1	1
Kc	46(15)	4	17 079	24.2	36.4	44.1	104.7	2
Am	4	2	1 122	2.1	18.2	2.9	23.2	3
Bg	2(1)	1	339	1.1	9.0	0.9	11.0	4
Ai	253	1						

(6) *Acanthus ilicifolius* small community: *Acanthus ilicifolius* grows vigorously in the mud beach of creek. It was beginning to flower when we surveyed the area. It is a small community surrounded by *Panicum repens* and *Cynodon dactylon*, etc., with a height of 90 cm, and a density of 10 ind./m².

4 Discussion

4.1 Distribution of vegetation

Investigation and analysis of transects show that the mangroves present a zonation from the higher tidal zone to the lower tidal zone and from the estuary to the bay. In the longest transect-T3 (295 m long), there are many narrow ecotones. And the middle zone is dominated by *Avicennia marina* association for historical reasons. Lugo (1980) claimed that mangrove forests usually have sharp ecotones with adjacent ecosystems because the saline condition of the mangroves habitat is tidally and topographically determined^[8]. Wherever the tide transports the saltwater inland, the mangroves will colonize available sediments. But slight topographic changes (in centimeters) can create a sharp ecotone where saline and tidal conditions end. Depending on the resulting hydrology or edaphic conditions, the adjacent ecosystem can be a freshwater wetland, a saline flat, a terrestrial ecosystem, or any combination of these. The transition from mangrove to non-mangrove habitats can be sharp as indicated or gradual, where mangroves become less and less important as the salinity and tidal regime change away from those that delimit the range of mangroves growth and survival. T1 and T2 exhibit a clear zonation pattern, where the density of trees is lower, but the mDBH of trees higher. The results show that the woodland has been protected for a long time. T4 is characterized by an early successional state of community and habitat: the distribution of species alters gradually, with higher tree density, lower mDBH and fewer species. It shows that the mangrove associations, which distribute mainly in the Shenzhen estuary, are formed lately. The research on the habitat of mangroves shows that *Aegiceras corniculatum* grows on the beach where the topsoil is spongy and deep, and *Avicennia marina* can grow in the sandy soil of beach^[37]. This pattern reveals the heterogeneity of microtopography and hydrological features. It is a basis of biodiversity in this region.

4.2 Components of mangroves

According to the investigation on this area, there are 6 species of mangrove plants and 3 species of semi-mangrove plants in the Futian Nature Reserve. It seems that the mangroves are poor in species richness. Actually, it is all the same throughout the world. Lugo *et al.* (1988) proposed that fewer species are normally found in freshwater forested wetlands^[38]. Values in these forests range from 1 to 23 species per hectare with averages of 8.3 and 6 species per hectare for riverine and basin freshwater wetlands, respectively. Mangroves are even more species-poor and in fact are among the most species-poor forest ecosystems in the tropics. Later Jansen (1985) found that mangroves often contain no understory plants^[39], we can also encounter this situation in this area or in northern distribution range of mangroves in China^[23]. Why? It may be due to the fact that its habitat conditions in the mangrove stands make it extremely difficult for non-halophytic and non-wetland plants to grow and reproduce. Even so, the mangroves hold more and more benthic animals and birds^[29, 40]. Steinke *et al.* (1990) found the leaves of *Avicennia marina* and *Bruguiera gymnorhiza* harbouring 20 ~ 25 species of fungi^[41]. Otherwise, as *Derris trifoliata* just could be seen in mature quadrats, we propose it as an indicator species for mangroves succeeding toward the terrestrial forest.

4.3 Development of mangroves

Investigation shows that there are few seedlings in the *Avicennia marina* association, and its survival curve fits the Deevey type II. As there are many *Derris trifoliata* in this association, it is indicated that this association has reached a mature stage. On the other hand, there are many *Aegiceras corniculatum* and *Kandelia candel* saplings and seedlings in the understory of other 5 associations, and their survival curves fit the Deevey type III. It is indicated that *Kandelia candel* associations or *Kandelia candel* + *Aegiceras corniculatum* associations are in the developing succession stage. In the mature mangroves, trees are about 20 years old and reach a canopy height of approximately 4 to 5 m, and toward the estuary, the trees are becoming younger and dwarfed. Mangroves may develop from the Shenzhen Bay firstly, as the *Avicennia marina* association develops, litter falls and debris aggrades around this vegetation, and it helps *Kandelia candel* and *Aegiceras corniculatum* to settle. Then the mangroves expand seaward and toward the Shenzhen estuary.

4.4 Importance of mangroves

Mangroves ecosystem is a buffer system where the mud deposits slowly, and the organic matter is decomposed slowly. Mangroves distributing in the polluted estuary areas have some anti-pollution capability. This system can change the pollution matter into unsolvable matter by soil deposition and absorption as ion-exchange reaction happens.

5 Conclusions

(1) This region is an important wetland area supported by 6 associations of mangroves: *Kandelia candel* association, *Avicennia marina* association, *Aegiceras corniculatum* association, *Kandelia candel* + *Aegiceras corniculatum* association, *Aegiceras corniculatum* + *Kandelia candel* association and *Acanthus ilicifolius* association.

(2) 6 Species of mangrove plants, 3 species of semi-mangrove plants and an accompany species appear in this research area.

(3) From transect I to transect IV, the importance value of *Avicennia marina*, *Bruguiera gymnorhiza* and *Kandelia candel* decreases, and that of *Aegiceras corniculatum* increases. In this area, the *Kandelia candel* population and the *Aegiceras corniculatum* population are developing populations with many seedlings and saplings, but the *Avicennia marina* population is in a mature stage with few seedlings and not so many total individuals.

(4) According to this research, we suppose that *Aegiceras corniculatum* should be developed in the estuary and the *Avicennia marina* association should be protected.

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Fractal Characteristics of Population Canopy Structure of the Mangrove, *Bruguiera gymnorhiza* (L.) Lamk*

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Abstract The fractal characteristics of the canopy structure of *B. gymnorhiza* population are investigated by fractal dimension analysis in the National Shankou Mangrove Nature Reserve. The 3-year-old branches have box dimensions between 1.22 and 1.55, showing the complexity degree of branching structure and the ability of occupying and utilizing ecological space. It may be considered that fractal dimension provides a useful index for the study of light utilization efficiencies and growth processes of *B. gymnorhiza*. Calculated by using the two-surface method, the fractal dimensions for the crown pattern of individuals with ages of 20 to 50 years range from 2.21 to 2.54, indicating that the filling degree of foliage to a tree crown is relatively low and *B. gymnorhiza* has the property of a sun plant. Along with the increase of ages of individuals, the filling degree of foliage to a tree crown changes from high to low, and so does the fractal dimension. The box dimensions obtained from the grayscale curves of population canopy are between 1.47 and 1.61. The greater the box dimension, the more loosely organized the canopy spatial structure, and the more the light spots. The canopy structural information and complexity of a population can be effectively captured by box dimensions obtained from canopy grayscale curves.

Keywords Mangrove, *B. gymnorhiza* population, canopy structure, fractals

Bruguiera gymnorhiza (L.) Lamk. is an adspersed thermophilic mangrove species in the coastal mangrove swamps, occurring along the coasts of Eastern Africa, Asia, Oceania, etc. In China, it naturally distributes in Hainan, Guangxi, Guangdong, Fujian, Taiwan and Hongkong. Functioned as wood production, prevention from tides and waves, protection of dykes, etc., *B. gymnorhiza* is an important tree species for the construction of coastal ecological engineerings. So far, research into the ecology of *B. gymnorhiza* has concentrated mostly on matter circle, energy flow, spatial pattern, genetics, evolution, tree breeding, silviculture, etc. with a little on seedling biomass and fractal characteristics of patterns^[1-3]. In order to assess its new structural information and to further grasp its biological and ecological characteristics, fractal theory is applied to the canopy structure of *B. gymnorhiza* at the three levels of branch module, individual crown and population canopy.

1 Study areas

Field research has been conducted in the National Shankou Mangrove Nature Reserve of China (21° 28' ~ 21° 37' N, 109° 37' ~ 109° 47' E). The reserve has a lower subtropical monsoon

marine climate. The mean annual air temperature is 22.9 °C. The absolute maximum air temperature is 38.2 °C, and the absolute minimum 1.5 °C. The mean annual precipitation is 1 573.4 mm, of which 80 % ~ 85 % occurs during the months of April through September. Local tides have a normal-diurnal regime with an average of 2.53 m and a maximal range of 6.25 m. The mean annual sea-surface temperature is 23.5 °C, salinity 20 ~ 23, and pH value 7.6 ~ 7.8. The total area covered by mangroves in the reserve is estimated at about 730 hm². The main types of mangrove communities are *B. gymnorrhiza* community, *Rhizophora stylosa* community, *Kandelia candel* community, *Excoecaria agallocha* community, *Aegiceras corniculatum* community, *Avicennia marina* community *etc.*^[4]

Data for this study are collected from *B. gymnorrhiza* community, which grows in a narrow fringe on the landward region of the mangroves. The community is 4 ~ 7 m in height, with a canopy coverage of 50 % ~ 85 %. The upper canopy is dominated by *B. gymnorrhiza*, with a few *R. stylosa*, *K. candel*, *etc.* mixed. The understory is often composed of *B. gymnorrhiza* seedlings; in some regions, where the natural regenerative processes of *B. gymnorrhiza* are much better, there are also many numbers of *B. gymnorrhiza* saplings. Otherwise, on a few sites, the understory is dominated by *A. corniculatum*.

2 Methods

2.1 Branching pattern

The common 3-year-old branches of *B. gymnorrhiza* are collected by using 0.5 m × 0.5 m sampling square frame. Foliage are first removed from the sampled branches, then the branches without leaves are photographed to obtain a 2-dimension branch projective image. The branch image is covered with a grid of square boxes of side length, δ , and the number of boxes containing part of the branch, $N(\delta)$, counted. The side lengths, δ , chosen here are 0.050, 0.056, 0.063, 0.071, 0.083, 0.100, 0.125, 0.167 and 0.250 m, respectively. The fractal dimensions are given by the following equation^[5, 6]:

$$D = - \lim_{\delta \rightarrow 0} \frac{\log N(\delta)}{\log \delta} \quad (1)$$

2.2 Crown pattern

In the reserve, most crowns of *B. gymnorrhiza* trees are usually more regular and ellipse-shaped, only a few are hemisphere-shaped or conoid-shaped. Because young *B. gymnorrhiza* individuals often grow in clumps around their parent trees, crowns of these young individuals interweave together, which result in the difficulty of measuring the crowns. In order to prevent extremely distorted individuals from unduly influencing the results, 55 individuals with regular ellipse-shaped crowns and ages above 20 *a* are selected. For each sampled individual, tree height (H), diameter at breast height (DBH), width of the maximum (d_1) and minimum (d_2) axis of crown, length of crown (L), *etc.* are measured. A total of 10 out of the 55 individuals are cut down to harvest the foliage.

The power regression is established between foliage dry weight (W) and DBH and H of the sampled individuals, which is used to estimate the foliage dry weight of other individuals.

Crown volumes (V) are calculated by the following equation^[7]:

$$V = \frac{4}{3} \pi abc \quad (2)$$

Where, $a = \frac{1}{2} d_1$, $b = \frac{1}{2} d_2$, and $c = \frac{1}{2} L$.

Fractal dimensions of crowns are calculated by the two-surface method^[8-10]:

$$\log W = \log b + D / 3 \log V \quad (3)$$

2.3 Canopy

In terms of the scaling ranges of spatial autocorrelation of *B. gymnorhiza* individuals being between 1.3 and 14.7 m, one 15 m community segment composed only of *B. gymnorhiza* individuals is selected in each of the four plots, marked and then photographed. The grayscale intensity values along a transverse line path in the images obtained are computed using the image processing toolbox of MATLAB^[11]. Two-dimensional plots of grayscale intensity values versus the distance along the line segment are created, and their fractal dimensions calculated by Equation (1).

3 Results and Analyses

3.1 Fractal characteristics of branching pattern

Branches are an important module of the morphological structure of a tree. Branching angle with the stem, branching method, etc. determine the spatial pattern of branching and the shape of crowns. The results of field investigations made in the reserve show that in the architecture of *B. gymnorhiza* trees two types of branching can be distinguished. One type is that after a bud produces a shoot, usually only one lateral bud on the lower side of the shoot produces one lateral shoot, which in turn produces mostly one, seldom two, new lateral shoots. The resulted branching pattern is showed as Type A (left panel) in Fig.1. Branching method of this kind is usually more regular, forming

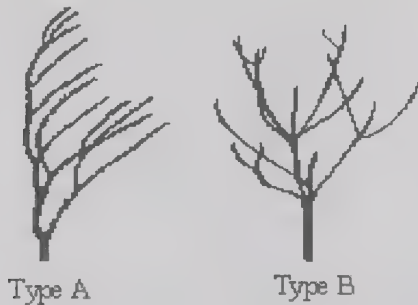


Fig.1 Common branching patterns of *B. gymnorhiza* trees (scanned from photograph)

plagiotropic branches. The branches of this type are morphologically similar, more or less, to dichotomizing ones, and have a very obvious self-similar property. Another type is showed as Type B (right panel) in Fig.1. After terminal buds produce terminal shoots, lateral buds produce lateral shoots and usually two pairs of such shoots intergrowth, with a morphology similar to whorl growth. The total lengths and internode lengths of lateral shoots are usually greater than those of terminal shoots. The branch formed is spherical or semi-spherical in shape, and has a higher self-similarity in terms of the morphology of its tiers of branching.

In order to make a fractal analysis, 3-year-old type A and type B branches of *B. gymnorhiza* are

selected based on their self-similar structural characteristics. For each type of branching, the typical branches with long, middle and short internodes are sampled, respectively. The 2-dimension projective image of each sampled branch is covered by a grid. The log-log relationship between box sizes, δ , and the number of non-empty boxes, $N(\delta)$, is illustrated in Fig. 2. The results of linear regression

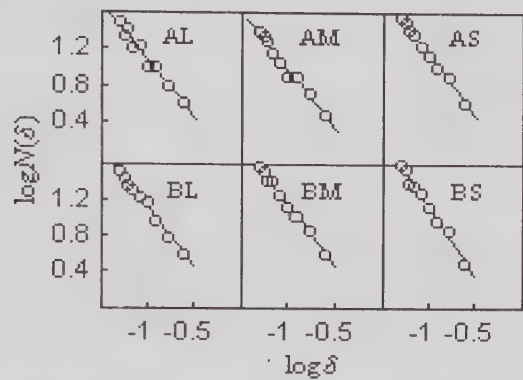


Fig. 2 The $\log \delta - \log N(\delta)$ relation for the branching patterns of *B. gymnorhiza* trees

analysis indicate that the linear relations between $\log \delta$ and $\log N(\delta)$ are significant at a probability level of 0.01 (Tab. 1). They suggest that although different branches vary in internode length,

Tab. 1 Box dimensions for the branching patterns of *B. gymnorhiza* trees

Item	Type of branches					
	AL	AM	AS	BL	BM	BS
Fractal dimension	1.229 0	1.287 2	1.300 3	1.308 8	1.389 1	1.540 3
Correlation coefficient (R^2)	-0.981 3	-0.991 1	-0.997 0	-0.994 5	-0.997 8	-0.995 2
Significant level (P)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

structure model and complexity degree, the spatial arrangements of branching show a self-similarity in structure and possess fractal characteristics. The fractal dimensions for Type A branches of long (AL), middle (AM) and short (AS) internodes are, respectively, 1.229 0, 1.287 2 and 1.300 3, with an average of 1.272 2, while those for Type B branches of long (BL), middle (BM) and short (BS) internodes are , respectively, 1.308 8, 1.389 1 and 1.540 3, with an average of 1.412 7 (Tab. 1). Under the same conditions, fractal dimensions of Type B branches are greater than those of Type A branches, because the structure of Type B branches is more complex than that of Type A branches and

in the same scale range the spatial occupation degree of Type B branches is higher than that of Type A branches. For both Type A and Type B branches, the spatial arrangement structures of longer internode branches are usually looser, and correspondingly have smaller fractal dimensions. The fractal dimensions show a change in branches in internode length order of long < middle < short. Therefore, values of fractal dimensions reflect the spatial structural complexity and the spatial occupation and utilization ability of branches of *B. gymnorhiza*. The greater the fractal dimensions, the more complex the branching structure, the stronger the spatial occupation and utilization capability, and the higher the light energy efficiency.

3.2 Fractal dimensions of crown patterns

The power regression relationship between DBH and tree height and foliage mass of *B. gymnorhiza* individuals is given by:

$$W = 0.05225 (DBH^2 H)^{0.65489} \tag{4}$$

Because tree crowns are composed of branches, which have a fractal structure, and their whole structures are similar to branching structures, fractal dimensions can be viewed as a new parameter illustrating the crown structure^[12]. Table 2 gives the averages of foliage mass, crown volume, *etc.* of

Tab. 2 Averages of the measured data of *B. gymnorhiza* individuals and fractal dimensions of crowns

Age class (a)	No. of samples	Plant height (m)	DBH (cm)	Crown width (m)	Crown length (m)	Crown volume (m ³)	Foliage mass (kg)	Fractal dimension	Correlation coefficient (R ²)
20~30	25	4.3	12.8	3.0	2.1	9.05	4.14	2.536 6	0.839 5**
30~40	15	4.6	18.4	3.4	2.0	11.46	6.07	2.321 8	0.781 4**
40~50	15	4.1	21.6	3.5	1.9	11.62	6.56	2.213 5	0.793 7**

**Significant at the 0.01 probability level

55 *B. gymnorhiza* individuals with ages of 20~50 a. The values of crown volume and foliage mass of these individuals must be log-transformed in order to calculate fractal dimensions of tree crowns, and the log *V*— log *W* relations obtained are illustrated in Fig. 3. Linear regression fits a linear function of Equation (3) to the log *V*— log *W* data. All correlation coefficients are significant at the 0.01 probability level, indicating that crowns of *B. gymnorhiza* trees have a fractal property. Fractal dimensions for the crowns of trees of three age classes of 20~30 a, 30~40 a and 40~50 a are, respectively, 2.5366, 2.3218 and 2.2135, which in fact quantify the filling degree of foliage to a tree crown. A fractal dimension of 2 suggests that a crown's foliage mass is proportional to the crown's surface area, indicating that the filling degree of foliage to the crown is lowest and foliage distributes on the crown's surface. A fractal dimension of 3 suggests that the foliage mass is proportional to the volume of the crown, indicating foliage is evenly distributed throughout the crown. Hence, the fractal dimensions of tree crowns range from 2 to 3^[5, 8-10]. Table 2 shows that along with the increase of individual ages, the filling degree of foliage to a tree crown changes from high to low, and so does the

fractal dimension. These change processes, in fact, are closely related with the biological and ecological characteristics of *B. gymnorhiza*. Younger individuals of *B. gymnorhiza* usually, grow vigorously, and have more foliage, which have a higher filling degree to crowns. However, with their ages increasing, the growth of individuals gradually weakens, even stops, as a result of which foliage of such an individual have a lower filling degree to crowns. Therefore, the fractal dimensions of crowns can be better indicative of foliage distribution, tree endurance, crown class, photosynthetic ability, *etc.*

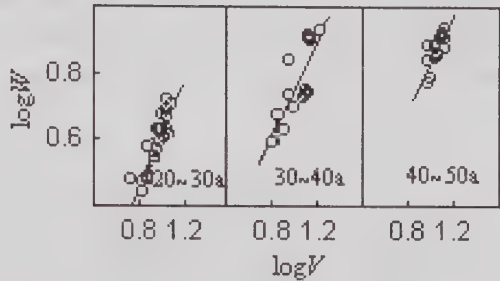


Fig. 3 The $\log V$ — $\log W$ relation of crowns of *B. gymnorhiza* trees

3.3 Fractal characteristics of canopy structure

Figure 4 shows the grayscale curves of canopy structures of *B. gymnorhiza* populations in Q1, Q2 and Q3. Each curve is covered by a grid, and the log-log relationship between box sizes, δ , and

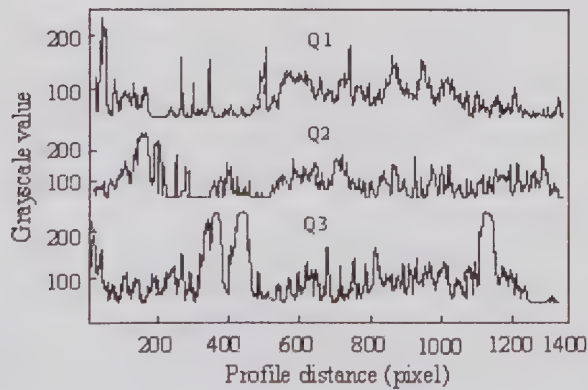


Fig. 4 Grayscale curves of *B. gymnorhiza* population canopy

the number of non-empty boxes, $N(\delta)$, is illustrated in Fig. 5. There is an evident linear relationship between them. The correlation coefficients of linear regression analysis are found to be 0.839 5,

0.781 4 and 0.793 7 for Q1, Q2 and Q3, respectively, significant at the 0.01 probability level, indicating that the canopy structure of *B. gymnorhiza* populations has a fractal property. Calculated by Equation (1), the box dimensions are respectively 1.475 2, 1.600 2 and 1.496 0, with a size order of $Q1 < Q3 < Q2$. The higher the box dimensions, the more complex the grayscale curves, the more loosely organized the canopy structures, and the more the light spots. Based on field measured data, the mean relative light intensity for these three plots are respectively 48.7 %, 52.0 % and 59.3 %, and the fractal dimensions for light intensity distribution are respectively 1.850 7, 1.677 8 and 1.817 3, with a size order of $Q1 < Q3 < Q2$. These analyses imply that structural characteristics of a canopy can be investigated by measuring the fractal dimensions either of its light intensity or of its grayscale curves. Therefore, the canopy structural information and complexity may be quantitatively disclosed by an analysis of canopy image data.

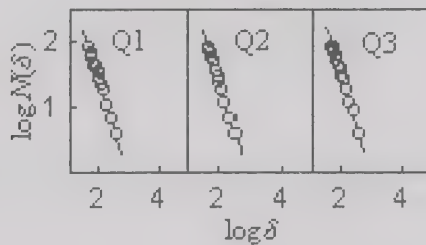


Fig. 5 The $\log \delta - \log N(\delta)$ relation of *B. gymnorhiza* population canopy

4 Conclusions

1) The branching pattern of *B. gymnorhiza* is a kind of fractal structure, possessing self-similar characteristics. The box dimensions of 3-year-old branches range from 1.22 to 1.55, which disclose the complexity of branching structure and the ability of occupying and utilizing ecological space. It can be considered that the fractal dimension provides a useful parameter for the study of light utilization efficiencies and growth processes of *B. gymnorhiza* and basis for studying the fractal property of population canopy at a larger scale level.

2) The crown patterns of *B. gymnorhiza* individuals have self-similar properties, which can be quantified by fractal dimensions. The fractal dimensions for the crown patterns of individuals with ages of 20 to 50 years range from 2.21 to 2.54, which indicate the filling degree of foliage to crowns. Along with the increase of individual ages, the filling degree of foliage to crowns changes from high to low, and so does the fractal dimension. These change processes, in fact, are closely related with the growth laws of *B. gymnorhiza*.

3) Based on the results of the analysis of grayscale curves of *B. gymnorhiza* population canopy, it can be concluded that the population canopy has fractal characteristics. The box dimensions are between 1.47 and 1.61. The higher the box dimensions, the more loosely organized the canopy structures, and the more the light spots. There is reason to believe that the box dimensions obtained from the grayscale curves of population canopy can effectively disclose the structural information and

complexity of population canopy.

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Characteristics of Growth Rate of Coral *Porites* from Sanya Bay, Hainan Island and its Relationship to Environmental Variables

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Abstract The time series of annual and seasonal growth rate of two coral *Porites*, collected at different sites of fringe reef in the Sanya Bay, Hainan Island have been obtained by analyzing X-radiograph of skeletal band. There are obvious seasonal variations of the growth rate in two corals, the average low rate in winter and the average high rate from spring to autumn. Compared with the time series of environmental variables, the coral growth rate is only correlated statistically with seawater temperature and not related to rainfall and sunshine. Furthermore, the growth rate in spring and summer is correlated directly with seawater temperature of the winter-early spring (between December and March) and the other seasonal growth rate has no relationship with seasonal variations of seawater temperature. We propose that seawater temperature is one of the factors affecting the coral growth rate in the area and the low seawater temperature is a primary control of the seasonal growth rate.

Keywords skeletal band of coral *Porites*, growth rate, environmental controls

1 Introduction

Hermatypic coral which lives in the tropic ocean is a sort of material with high resolution containing geological signals, having become a hotspot in study on tropic oceanic environment and global change. Because of the coral's biological and ecological features, the growth of coral is characteristic of distinct annual skeletal band. The ecological amplitude of hermatypic coral is narrow, and the coral growth is restricted severely by environmental conditions such as seawater temperature, salinity, sunlight intensity, water depth, sediment load and seawater dynamics *etc.*^[1]. The environmental variables influencing the coral growth are synthetic and pronounced. The correlation between coral growth and environment variables has been studied in different ocean regions all over the world. The biological and environmental controls of coral skeletal growth are relatively complicated. The growth of various coral species in different ocean areas is influenced diversely by environmental factors. Seawater temperature and sunshine are generally agreed to be the most likely controls causing variations in the coral growth^[2-9]. These factors, however, can only explain partly the characteristics of coral growth; it is unavailable to critically assess other potential controlling factors. Study on the growth of coral *Porites* in the South China Sea in recent years shows that the coral

growth rate has remarkable linear correlation with surface seawater temperature and the linear correlation is attempted to reconstruct the surface seawater temperature for hundreds of years^[1]. Understanding the primary environmental controls of coral growth is an important foundation for establishing climatic proxy of coral growth and reconstructing the history of past environmental change.

In this paper, we present preliminary results of study on the growth rate of coral *Porites* collected from two fringe reef areas in the Sanya Bay in the south of Hainan Island. We intend to illustrate, first, the characteristics of coral growth rate which is extracted from the X-radiographs of skeletal bands; second, possible statistical correlations of annual and seasonal growth with local environmental factors and the primary environmental controls for coral growth.

2 Materials and methods

We investigated fringe reef areas in the Sanya Bay in the southern Hainan Island in April 2001 and collected two massive specimens of coral *Porites* living at about 2~3 m depth at Luhuitou and Ximao Island (Fig. 1). The LHT specimen is 40 cm long, collected at the fringe reef about 200 m from the northwestern coast of Luhuitou. The XD4 specimen is 110 cm long, collected at the east coast of Ximao Island about 11 kilometers from the west of Luhuitou. The original massive coral of XD4 was dredged up from the small harbor by local people in 2000. Both LHT and XD4 belong to species of *Porites lutea*.

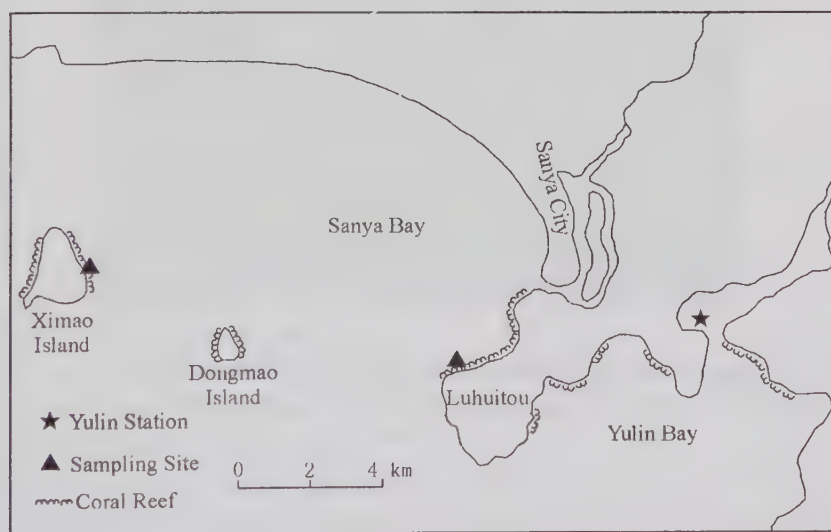


Fig. 1 Fringe reef distributions in the Sanya Bay, Hainan Island and sampling sites

The coral skeleton of LHT and XD4 is sliced into 1 cm thickness along the main growth axis of the coral and X-radiographed. The negative X-radiographs of coral skeleton are scanned directly into computer and transformed into positive X-radiographs. Then we obtain the integrated digital image of

the coral skeletal bands by piecing together positive X-radiographs of different skeletal parts.

The images of LHT and XD4 coral skeleton present a clear distribution of dark and light layers (Fig. 2). The narrow dark layers are the high-density band with a small growth rate, and the wide light layers are the low-density band with a large growth rate. It is commonly accepted that the coral skeleton grows with distinct seasonality, and the pattern of high and low density band constitutes the seasonal alternation of skeletal band. LHT was collected in April 2001, so the topmost light low-density band was formed at the same time and the first dark high-density band beneath the light low-density band should have been formed in winter between 2000 and 2001. Hence, it is also ascertained that the dark high density band of LHT and XD4 is formed in winter and the light low density band is formed in other seasons from spring to autumn, the same as the skeletal band pattern of coral *Porites* in other regions of the South China Sea^[1]. The darkest layer of the high-density band is regarded as the annual boundary of the skeletal band, and the growing ages of skeletal bands are counted for LHT and XD4 (Fig. 2). Removing the disordered bands in the bottom part, the skeletal bands of LHT and XD4 have spanned intervals of 15 years (1987—2001) and 44 years (1957—2000) respectively.

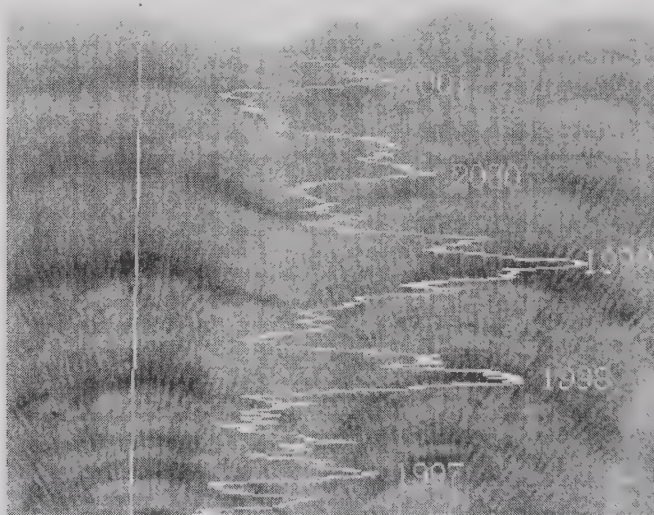


Fig. 2 X-radiograph image of upper skeletal band of coral LHT
(Curve shows variations of image gray scale along the main growth axis.)

In the previous study^[1], the growth per year was measured directly on the skeletal X-radiograph, but this method could only obtain the annual growth rate, and the biggest error has existed in the measuring process. Using image analysis of computer, we attempt to establish a new method in this paper to obtain the growth rate with high resolution and decrease the errors in measurement. By using the image analysis program, the data of pixels in skeletal image are read along the main growth axis and transformed into the actual width of skeletal band according to the image resolution. Then the width of skeletal band per year on each of the corals, namely annual growth rate, is calculated easily. In order to reduce disturbance caused by impurities in the coral skeleton, influences in X-radiography

and scanning processes and other uncertain effects in the coral growing process, several pixels at the same growth layer paralleling the main growth axis are read and averaged, so as to insure reliability of the growth data. In addition to this annual data, we have followed the time series of skeletal growth rate. Since the high-density band is narrow and the low-density band is wide, according to the inverse correlation between the image density and the growth rate, the time series of growth rate are obtained by interpolation of image gray levels and ages of skeletal band. Because the skeletal band appears seasonal and the high-density band in winter spans two annual skeletal bands, the interpolating interval of annual band is season. The time series of the seasonal growth rate of LHT and XD4 are calculated and showed in Figure 3.

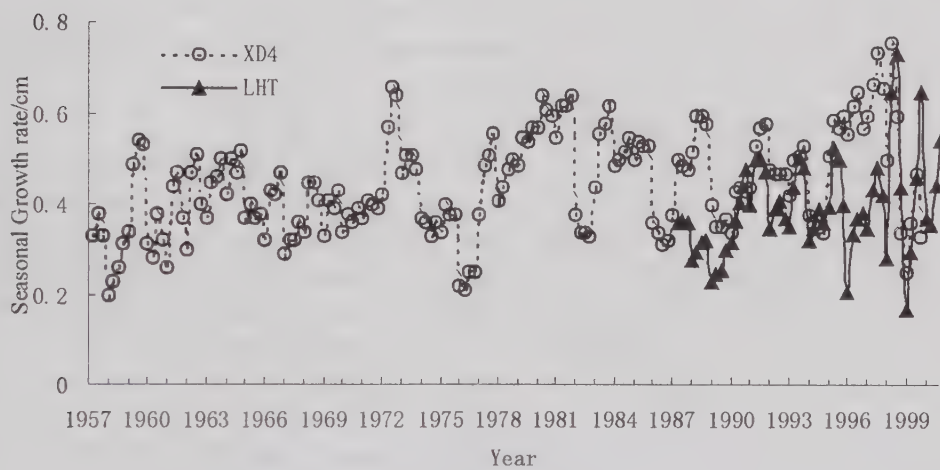


Fig. 3 Time series of seasonal growth rate of LHT (1987—2000) and XD4 (1957—1999)

3 Results

3.1 Annual and seasonal growth rates

LHT was 1.57 cm/a for the average annual growth rate from 1987 to 2000, and 2.12 cm/a for the maximum of annual growth rate in 1998 and 1.03 cm/a for the minimum annual growth rate in 1989. The average annual growth rate of XD4 was 1.78 cm/a from 1957 to 1999; The annual growth rate ranged from a minimum of 0.87 cm/a in 1976 to a maximum of 2.66 cm/a in 1997. The autocorrelation coefficients at 1 a lag of annual growth rate of LHT and XD4 were only 0.12 and 0.18 respectively, indicating that the year-to-year persistence of the coral growth was not evident and had little influence on the annual growth rate.

The growth rate is characteristic of the seasonal variations in LHT and XD4. The growth rate in winter is lower than that in other seasons. The average seasonal growth rate of LHT is 0.31 cm in winter, 0.40 cm in spring, 0.44 mm in summer and 0.43 cm in autumn respectively. The average seasonal growth rate of XD4 is 0.40 cm in winter, 0.46 cm in spring, 0.47 cm in summer and 0.46 cm in autumn respectively. The average growth rate in winter is about 0.06 ~ 0.11 cm less than that from

spring to autumn in both corals.

Figure 3 presents the time series of seasonal growth rate of LHT and XD4. Both seasonal growth rate series display similar features and several corresponding stages over the period of 1987—1999. For example, Fig. 3 shows apparent declines in LHT series during 1988 to 1989, 1991 to 1992 and 1993 to 1994 while XD4 series shows declines over the same period. The increase of growth rate in 1989—1991 and 1995 appears in LHT and XD4 series respectively. Moreover, Both LHT and XD4 growth rates show the highest rate in summer and autumn of 1998 and the lowest rate in winter of 1999 — 2000. A correlation analysis is also used to quantify the similarity of the two series within the same period of 1987 — 1999. A positive correlation is obtained for LHT and XD4 by the correlation coefficient of 0.38, significant at 0.01 level. Although there are differences in the coral individual growth of LHT and XD4, both the comparison and correlation analyses demonstrate that seasonal variations of the growth rate of LHT and XD4 share common features. These suggest that the time series of growth rate are reliable, and that the environmental effects are relatively consistent on the growth of two coral *Porites* in Luhuitou and Ximao Island.

3.2 Correlations with environmental variables

Seawater temperature and sunshine are generally regarded as the primary environmental factors controlling variations of coral growth rate^[2-9]. We have obtained the historical records of several environmental factors including seawater temperature, rainfall and sunshine hours from 1961 to 1999. The seawater temperature and rainfall data by month are archived in the Yulin oceanic hydrological station in the Yulin Bay about 8 km from the northeast of Luhuitou and the sunshine hours data by month are archived in the Sanya City Weather Station. Monthly means of seawater temperature, rainfall and sunshine hours are averaged into seasonal and annual values for each year to construct historical time series.

Sanya Bay, near 18° N, lies in the southern margin of Hainan Island. This region is characterized by a tropical monsoon climate. The seasonal variations of seawater temperature, rainfall and sunshine hours tend to be the major climatic characteristics of the region. The average annual seawater temperature at the Sanya Bay was 26.9 °C over the period of 1961 — 1999. The average monthly seawater temperature reached the maximum of 29.5 °C between May and September and the minimum of 23.2 °C between December and February; the average seasonal variation was over 6 °C. The average annual precipitation was 1 278 mm in this region from 1961 to 1999. A moist summer monsoon with a clear summer rainfall maximum occurred between May and October, and the average precipitation was 1 123 mm, 88% of the annual rainfall total. The dry condition generally occurred in the other seasons between November and February, and the average precipitation was only 155 mm. The average annual sunshine hours was 2 489 h over the period of 1961 — 1999; the high sunshine hours were averaged out at 229 h per month between May and August and the lowest sunshine hours at only 161 h per month in February. The annual cycle for the three environmental variables is given in Fig. 4. The seasonal variations of seawater temperature, rainfall and sunshine hours are matched by the seasonal variations of growth rate of LHT and XD4 which peak from spring to autumn and is the lowest in winter. Hence, the seasonal variations of environmental factors have important impact on the coral growth rate.

We have compared the time series of annual and seasonal coral growth rates of LHT and XD4 with those of the environmental data including seawater temperature, rainfall and sunshine hours respectively by correlation analysis. The statistical results are similar between LHT and XD4. The

correlation coefficients are $r = 0.68$ and 0.39 for the annual growth rates of LHT and XD4 with annual seawater temperature respectively, statistically significant at the $P = 0.05$ level, indicating that the annual growth rates of both LHT and XD4 vary positively with the annual seawater temperature. However, the correlation coefficients of annual growth rate with annual rainfall and sunshine are rather lower and have never passed the significant level test, indicating poor correlations between each other.

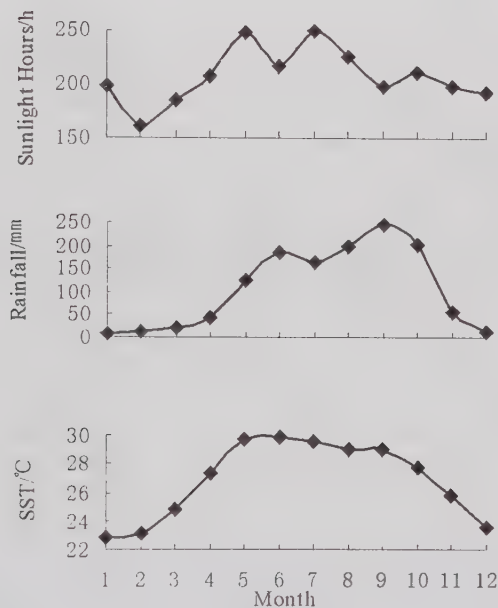


Fig. 4 Average monthly values of seawater temperature, rainfall and sunshine hours from 1961 to 1999 in the Sanya Bay

The similar statistical results have also been gotten between seasonal growth rate of LHT and XD4 and environmental variables. Only the growth rate in spring and summer correlates significantly with seawater temperature in winter and early spring. The correlation coefficients of spring growth rate with seawater temperature between December and March are 0.78 and 0.44 for LHT and XD4 respectively, significant at the $P = 0.01$ level. The correlation coefficients of summer growth rate with seawater temperature between December and March are 0.89 and 0.37 for LHT and XD4 respectively, significant at the $P = 0.01$ and $P = 0.05$ levels respectively. The correlation coefficients of growth rate of LHT and XD4 in autumn and winter with seasonal seawater temperature are rather low and have never passed the significant level test. Moreover, no statistically significant correlation is found between seasonal growth rate of LHT and XD4 and seasonal rainfall and sunshine hours.

Figure 5 illustrates the match of growth rate anomaly series of LHT and XD4 in spring and summer with seawater temperature anomaly series between December and March. The seawater temperature between December and March was lower than the average seawater temperature from

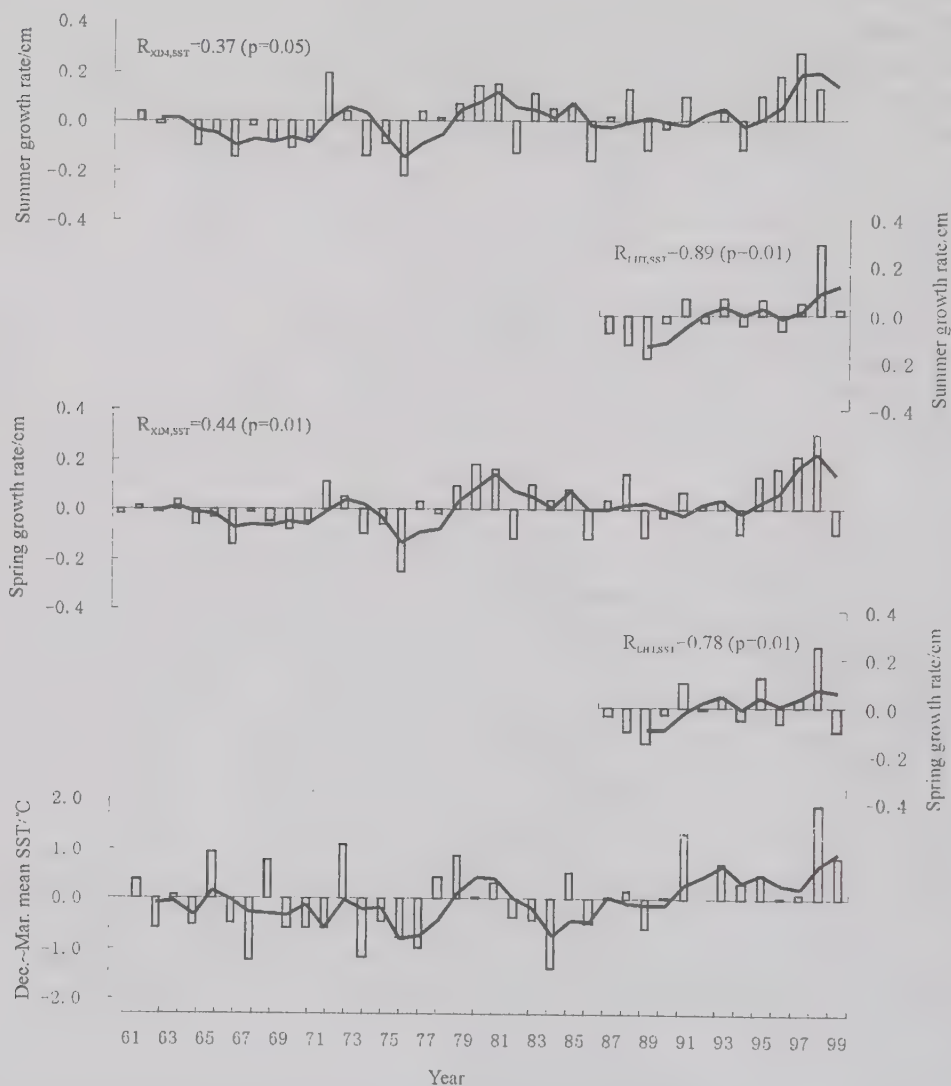


Fig. 5 Comparisons of anomalies of spring and summer growth rate of LHT and XD4 with anomalies of seawater temperature between December and March (The solid lines show the three years' smoothed averages.)

1961 to 1977 and from 1982 to 1990. Over the same periods, the variations of growth rate of XD4 in spring and summer were generally in phase with variations in seawater temperature between December and March. For example, the spring and summer growth rate was lower than the average from 1961 to 1978 and declined to the average rate level from 1982 to 1990. The seawater temperature between December and March presented a warm fluctuation and was higher than the average in the periods of 1978—1981 and 1991—1999; the seawater temperature between December and March in 1998 reached the maximum of 25 °C. The spring and summer growth rate of Xd4 increased beyond the

average rate in the two same periods and the spring and summer growth rates reached the maximum in 1998. The spring and summer growth rate of LHT was lower than the average from 1987 to 1990, corresponding to the low seawater temperature between December and March in the same period. The spring and summer growth rate of LHT increased to small extent from 1991 to 1999 and reached the maximum rate in 1998, in phase with the increases of seawater temperature in the same years. Therefore, the variations in the spring and summer growth rate of XD4 and LHT are coincident with those in seawater temperature between December and March.

4 Discussion

The growth of hermatypic coral is synthetically influenced by ambient environmental factors. Study has revealed the extreme conditions of environmental factors restricting coral growth^[1]. Many studies also show that the various coral species and corals in different locations are variously sensitive to environmental factors. The coral *Porites* of LHT and XD4 live at different sites with individual growing process, but the two corals have the same characteristics of annual and seasonal growth rates and good relations between each other, suggesting the commonness of environmental effects on coral growth in the Sanya Bay. The good correlation of seawater temperature with the coral growth rates of LHT and XD4 and the corresponding variations in them over the same periods reveal that seawater temperature exerts a major control on the growth of coral *Porites* in the Sanya Bay.

Although the seasonal variations of coral growth rate matched those of seawater temperature, rainfall and sunshine hours, the correlation analysis and comparison of time series show that the growth rates only significantly correlate with seawater temperature and have no correlation with rainfall and sunshine hours. These indicate that only seawater temperature variations are mainly responsible for growth rates, and rainfall and sunshine have little impact on coral growth. Laboratory studies show that the variations of seawater temperature can influence the anabolism of coral^[10, 11]. The coral anabolic activity intensifies when the seawater temperature rises and weakens when it lowers. This relation also influences the growth process of coral skeleton and varies the growth rate. The optimal seawater temperature of coral is 25 °C ~ 29 °C in the South China Sea and the seawater temperature higher than the range will restrict coral growth^[1]. The annual seawater temperature ranged from 24.9 °C to 27.0 °C from 1961 to 1999 in the Sanya Bay and the monthly average seawater temperature ranged from 22.8 °C to 29.9 °C. Both the annual and monthly average seawater temperature were within the optimal seawater temperature range, but the seasonal variations of seawater temperature may still influence the coral skeletal growth. Generally, rainfall influences the coral growth mainly through the direct effects of altered salinity. A low tolerance to wide fluctuations in salinity is thought to limit coral development. In the Sanya Bay, the adaptable salinity range for coral is rather wide; the salinity fluctuation caused by the annual and seasonal variations of rainfall is very small and never exceeds the adaptable salinity^[1]. So the rainfall variations' impact on coral growth is not evident like the seawater temperature. As is well known, the skeletal growth of hermatypic corals is correlated with the photosynthetic activity of the endosymbiotic zooxanthellae within coral tissues. Sunshine hours represent intensity of sunlight available for photosynthesis, and variations of sunlight intensity affect the coral growth by influencing photosynthesis of the zooxanthellae. The water depth of LHT and XD4 coral *Porites* is about 3 ~ 5 m and the corals can acquire enough sunlight in these depths, so the coral growth is not sensitive to annual and seasonal variations of sunlight.

Although the annual growth rates of LHT and XD4 have correlation with the annual seawater

temperature, it is still difficult to reveal the controlling effect on growth rate of seawater temperature, because there are seasonal differences in the relations between seasonal variation of seawater temperature and seasonal growth rate. In the seasonal variations of seawater temperature, only the temperature of winter-early spring (between December and March) has correlation with the coral growth rate, but the other season temperatures have no evident correlations with the growth rate. December ~ March is a period of the lowest seawater temperature in the Sanya Bay, and the average monthly seawater temperature ranges from 22.8 °C to 24.8 °C, less than the low limit 25 °C of optimal temperature for coral growth in the South China Sea, thus restricting the coral growth to a large extent. Hence, the coral growth is relatively sensitive to the variations of temperature below the optimal temperature and the growth positively correlates with the low seawater temperature in winter spring. The seawater temperature in other seasons (April to November) is rather high in the Sanya Bay and the monthly average seawater temperature ranges from 25.8 °C to 29.9 °C within the optimal seawater temperatures of coral growth, adapting to the coral growth easily. So coral growth is not sensitive to the variation in the optimal temperature range and the growth rate never presents an evident correlation with seawater temperature. In the Sanya Bay, consequently, the controlling effect of seawater temperature on the coral growth rate is mainly manifested in the restriction by the lower seawater temperature.

On the other hand, spring and summer growth rates of coral correlate significantly with the seawater temperature in winter-early spring, suggesting the distinct seasonal lag effect of low sea temperature on growth rate. Due to lack of details on the coral skeleton growing process and environmental effects, it is difficult to explain the lag effect of seawater temperature. Some studies have found that in addition to seawater temperature and sunshine, the seasonal variations in reproductive cycle and nutrient availability of coral also influence the coral growth rate^[8, 9, 12]. The lag effect of low seawater temperature in the Sanya Bay may be associated with the effect of low temperature on reproduction of coral. The low temperature in winter-early spring will decrease the coral reproduction and cause reduction of coral growth in spring and summer. Moreover, the low seawater temperature in winter-early spring also will weaken the reproduction and growth of plankton in seawater, thus resulting in the reduction of nutrient availability of coral in spring and summer and decreasing the coral growth.

In this paper, preliminary research findings have shown that low temperature is a primary environmental control on the seasonal growth rate of coral *Porites* in the Sanya Bay. However, the correlation coefficients between growth rate and seawater temperature are relatively low at the significant level, and the comparisons of seasonal variations also show incomplete correspondence and divergence between growth rate and seawater temperature, indicating that there is not complete linear correlation between seawater temperature and coral growth rate. Coral growth processes and environmental effects are quite complicated. Seawater temperature is not a unique environmental factor controlling coral growth. Besides biological influence of individual difference of coral growth, other environmental factors have also been complicated in the controls of coral growth. Furthermore, it is possible that there are synergistic effects from seawater temperature and other environmental factors. The poor understanding of the way in which environmental factors may affect the coral growth and uncertainties about mechanisms of the seasonal skeletal band formation mean that we need be more prudent in establishing climatic proxies and reconstructing paleoenvironmental history using the coral growth rate.

Acknowledgements

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Effect of Industrial Effluents on Embryos of Lefteye Flounder (*Paralichthys olivaceus*)

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Abstract The studies have been carried out in laboratory on the effect of dyeing, electroplating, pesticide effluents and their intermixture on embryos of lefteye flounder (*Paralichthys olivaceus*). The main toxic substances in dyeing effluent are aniline (20 mg/L) and phenol (24 mg/L). The main toxic substances in electroplating effluent are Zn (1 970 mg/L), Cu (9 mg/L) and Pb (7.5 mg/L). The main toxic substances in pesticide effluent are monocrotophos and phosphite. The test results indicate that the lowest concentrations of dyeing, electroplating, pesticide effluents and their intermixture, having significant effect on the hatch rate and development of *P. olivaceus* embryos, are 0.5 %, 0.15 %, 0.25 % and 0.25 %, respectively; and the incipient LC₅₀ of dyeing, electroplating, pesticide effluents and their intermixture are 3.38 % (2.29 % ~ 3.87 %), 0.81 % (0.71 % ~ 0.92 %), 1.57 % (1.37 % ~ 1.82 %) and 1.48 % (1.24 % ~ 1.76 %). Based on the incipient LC₅₀ values, the toxicity sequence of the three industrial effluents is in the order of electroplating effluent > pesticide effluent > dyeing effluent.

Keywords industrial effluent, lefteye flounder, embryos, toxicity effect

Industrial effluents are one of the main pollutants leading to marine pollution, especially in the littorals with highly dense population and developed industries^[1]. Dyeing, electroplating and pesticide effluents are all common industrial effluents, liable to enter inshore sea area. Generally, the supervision of effluents could be carried out through chemical analysis. The determined results, however, cannot directly reflect the effects of effluents on aquatic organisms. In this respect, bioassay methods are provided with the advantage of immediately determining the toxicity of the effluents to aquatic organisms.

Many laboratory studies have demonstrated the lethal effects of heavy metals and organic phosphorus pesticides on marine life^[2, 3], but studies on the toxic effect of dyeing, electroplating, pesticide effluents and their intermixture on fish in the early life stages have seldom been seen.

Lefteye flounder (*Paralichthys olivaceus*) is an economically important seawater fish species in the Bohai Sea and Yellow Sea. Many particular research findings related to the early morphological development and artificial seeding culture techniques have been published^[4, 5].

This study is carried out in laboratory on the effect of dyeing, electroplating, pesticide effluents and their intermixture on embryos of lefteye flounder (*Paralichthys olivaceus*).

1 Methods and Materials

1.1 Fish eggs

The eggs of lefteye flounder are got from the Haiyang Hi-Tech Research and Development Base of the Yellow Sea Fisheries Research Institute, and are all laid by the cultured parent fish.

1.2 Industrial effluents

Untreated dyeing, electroplating, and pesticide effluents have been collected from different related factories in Qingdao. The main toxic substances in dyeing effluent are aniline (20 mg/L) and phenol (24 mg/L). The main toxic substances in electroplating effluent are Zn (1 970 mg/L), Cu (9 mg/L) and Pb (7.5 mg/L). The main toxic substances in pesticide effluent are monocrotophos and phosphite. The mixed effluent is composed of the three industrial effluents in equal volume.

1.3 Test procedure

The tests are performed by adopting the 48 h static water method. Fifty fish eggs are transferred to glass beakers containing 500 mL test solution. The concentrations of effluents are set by geometric series. At the beginning of the test, most lefteye flounder embryos are in blastula stage.

Tests are run in triplicate. The seawater salinity is 33.0. Temperature is controlled at $(17 \pm 1) ^\circ\text{C}$. The photoperiod regime is a standard 12 h light : 12 h dark cycle.

At the end of tests, the egg hatch rate, larvae mortality, and embryo development rapidity in each beaker are checked and registered.

1.4 Data analysis

Differences of hatch rates between control and trial groups are assessed by t-test. The incipient LC_{50} values are calculated with the following methods:

Firstly, mortalities in each group are calculated by using the rectification formula:

$$\text{Mortality } (\%) = \frac{x - y}{x} \times 100 \%$$

Where: x = the hatch rate of the control group, y = the hatch rate of the trial group.

Then, the incipient LC_{50} values and the 95% confidence limit are calculated by using Moving Average-angle Method.

2 Results

2.1 Effect of dyeing effluents on the development of lefteye flounder embryos

The test results (see Tab. 1) indicate that the hatch rates of lefteye flounder embryos decline distinctly with the increase of dyeing effluent concentrations, while the hatch rates of the controls are all higher than 90 %. The hatch rate in the concentration of 1 % dyeing effluent is significantly lower than that in the control ($p < 0.05$). The hatch rates in the concentrations of 2 % ~ 4 % dyeing effluent are significantly lower than that in the control ($p < 0.01$). Embryos would die completely when the concentrations of dyeing effluent amount to 8 % ~ 16 %.

The incipient LC_{50} with 95 % confidence limit of dyeing effluent for lefteye flounder embryos is 3.38 % (2.29 % ~ 3.87 %).

Besides, it is found that the health of prelarvae is obviously affected with the increase of dyeing effluent concentrations. Prelarvae are not as lively as those in the control when the concentrations of dyeing effluent are 1 % ~ 2 %: some prelarvae move slowly, while some are in narcotism, or even in half moribund state.

Tab.1 Effects of dyeing effluent on the hatch of *P.olivaceus* embryos

Concentrations of effluent (%)	Hatch rates (%)	Mortality (%)	Incipient LC ₅₀	95 % Confidence limit
0	93 ± 3.0			
0.5	87 ± 2.8	6		
1	85 ± 0.6 ^a	9	3.38 %	2.29 % ~ 3.87 %
2	74 ± 2.1 ^b	20		
4	56 ± 4.3 ^a	40		
8	0	100		
16	0	100		

Note: a. Significant difference compared with the control ($p < 0.05$),
b. Significant difference compared with the control ($p < 0.01$).

2.2 Effect of electroplating effluents on the development of lefteye flounder embryos

Similar to the former test, the hatch rates of lefteye flounder embryos decline distinctly with the increase of electroplating effluent concentrations, while those of the controls are all higher than 90 % (see Tab. 2). The hatch rate in the concentration of 0.3 electroplating effluent is significantly lower than that in the control ($p < 0.05$). The hatch rates in the concentrations of 0.6 % ~ 1.2 % electroplating effluent are significantly lower than that in the control ($p < 0.01$). Embryos would die completely when the concentrations of electroplating effluent amount to 2.4 %.

The incipient LC₅₀ with 95 % confidence limit of electroplating effluent for lefteye flounder embryos is 0.81 % (0.071 % ~ 0.92 %).

Tab.2 Effects of electroplating effluent on the hatch of *P.olivaceus* embryos

Concentrations of effluent (%)	Hatch rates (%)	Mortality (%)	Incipient LC ₅₀	95 % Confidence limit
0	93 ± 2.7			
0.15	87 ± 2.3	5		
0.3	87 ± 2.7 ^a	9	0.81 %	0.71 % ~ 0.92 %
0.6	67 ± 6.9 ^a	28		
1.2	56 ± 4.3 ^b	68		
2.4	0	100		

Note: a. Significant difference compared with the control ($p < 0.05$),
b. Significant difference compared with the control ($p < 0.01$).

It is also found that most prelarvae in concentration of 0.3 % electroplating effluent are inclined to the beaker bottom, showing depressed activity. Partial death appears in concentration of 0.6 % electroplating effluents. Most prelarvae exposed to the concentration of 1.2 % electroplating effluent

die, or in half moribund state.

2.3 Effect of pesticides effluents on the development of left-eye flounder embryos

The test results (see Tab. 3) indicate that the hatch rates of lefteye flounder embryos are all significantly lower than those of the control, and decline distinctly with the increase of pesticides effluent concentrations. The hatch rates of the controls are all higher than 90 %. The hatch rate in the concentration of 0.25 % pesticides effluent is significantly lower than that in the control ($p < 0.05$). The hatch rate in the concentrations of 0.5 % pesticides effluent is significantly lower than that in the control ($p < 0.01$). Lefteye flounder embryos would die completely when the concentrations of pesticides effluent go up to 4 %.

The incipient LC_{50} value with 95 % confidence limit of pesticides effluent for lefteye flounder embryos is 1.57 % (1.371 % ~ 1.82 %).

Besides, most prelarvae in concentration of 2 % pesticides effluents die. Partial death appears in concentration of 1 % pesticides effluents, but many of the survivors are in wrong conditions, such as turning in the original place, or just trembling discontinuously.

Tab. 3 Effects of pesticide effluent on the hatch of *P.olivaceus* embryos

Concentrations of effluent (%)	Hatch rates (%)	Mortality (%)	Incipient LC_{50}	95 % Confidence limit
0	93 ± 2.0			
0.25	83 ± 4.4 ^a	11		
0.5	78 ± 1.3 ^b	16	1.57 %	1.37 % ~ 1.82 %
1	72 ± 1.2 ^b	23		
2	51 ± 1.9 ^b	45		
4	0	100		
8	0	100		

Note: a. Significant difference compared with the control ($p < 0.05$),
b. Significant difference compared with the control ($p < 0.01$).

2.4 Effect of mixed effluents on the development of left-eye flounder embryos

The test results (see Tab. 4) indicate that the hatch rates of lefteye flounder embryos decline distinctly with the increase of mixed effluent concentrations, while the hatch rates of the controls are all higher than 90 % (see Tab. 1). The hatch rate in the concentration of 0.5 % mixed effluent is significantly lower than that in the control ($p < 0.05$). When the concentrations of mixed effluent amount to 1 % ~ 2.5 %, the hatch rates are significantly lower than that of the control ($p < 0.01$). When the concentrations of mixed effluent go up to 5 %, it would cause left-eye flounder embryos to die completely.

The incipient LC_{50} value with 95 % confidence limit of mixed effluent for lefteye flounder embryos is 1.57 % (1.371 % ~ 1.82 %).

Most prelarvae in concentration of 2.5 % mixed effluents die. Partial death appears in concentration of 1 % mixed effluents.

Tab.4 Effects of mixed effluent on the hatch of *P.olivaceus* embryos

Concentrations of effluent (%)	Hatch rates (%)	Mortality (%)	Incipient LC ₅₀	95 % Confidence limit
0	93 ± 2.0			
0.25	83 ± 4.4 ^a	2		
0.5	78 ± 1.3 ^b	10	1.48 %	1.24 % ~ 1.76 %
1	72 ± 1.2 ^b	30		
2.5	51 ± 1.9 ^b	66		
5	0	100		

Note: a. Significant difference compared with the control (*p* < 0.05),
b. Significant difference compared with the control (*p* < 0.01).

3 Discussion and conclusion

(1) The test results indicate that dyeing, electroplating, and pesticide effluents have evident effects on the hatch and development of *P. olivaceus* embryos, main expressions being sluggish development, restraining hatch, depressing physiological function, inducing death and malformation. Based on the incipient LC₅₀ values, the toxicity sequence of the three industrial effluents is in the order of electroplating effluent > pesticide effluent > dyeing effluent.

(2) Toxic substances in industrial effluents from different sources have different concentrations, so it is hard to compare the toxicity of one with another. But as for the industrial effluents involved in this study, it is possible to make brief assessment of their toxicity based on the specific toxicants contained. In regard to the electroplating effluent, its main toxic substances are Zn, Cu and Pb. There have been a lot of study reports on the toxicity of those toxicants. Related studies^[6] indicate that 16 mg/L Zn would cause lefteye flounder eggs to die completely; flounder eggs exposed to 0.8 mg/L Cu would die completely in 42 h. The incipient LC₅₀ value of electroplating effluent derived in this study is 0.81 %, in which the concentrations of Zn, Cu and Pb are 15.96 mg/L, 0.073 mg/L, and 0.61 mg/L, based on their proportions. Obviously, the concentration of Zn is high enough to cause mass death of lefteye flounder eggs, while the concentrations of Cu and Pb are relatively low, not leading to the death of lefteye flounder eggs. It is evident that the toxicity of electroplating effluent reflects the toxicity of Zn mainly, and the joint action of Zn, Cu and Pb simultaneously.

(3) Dyeing, electroplating, and pesticide effluents are all compounds containing multi-toxicants, which just fall to three single kinds: heavy metals, organic phosphorus pesticides and phenol. So the intermixture could be simply regarded as mixed effluent containing the three kinds of toxicants. Thereby, the toxicity of intermixture should exhibit the joint action of the three effluents. According to the additive action model:

$$\frac{C}{LC_{50}} = \frac{C_1}{LC_{50_1}} + \frac{C_2}{LC_{50_2}} + \frac{C_3}{LC_{50_3}}$$

where: C, C₁, C₂ and C₃ = the concentrations of intermixture, dyeing, electroplating, and pesticide effluents, respectively.

LC_{50} , LC_{50}^1 , LC_{50}^2 and LC_{50}^3 = the expectant incipient LC_{50} , values of intermixture, electroplating, and pesticide effluents, respectively.

Then the expectant incipient LC_{50} of intermixture could be obtained, viz. 1.38 mg/L.

Based on the test results, the incipient LC_{50} of intermixture is 1.48 mg/L, which is 1.07 times the expectant incipient LC_{50} , indicating that the toxicity of intermixture exhibits additive action.

Surely, the joint action may show different forms along with different proportion of the three effluents, various exposure time and possibly different test organisms.

Acknowledgments

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In Situ* Determination of the Effect of Drilling Noise and Vibration on Growth of Grass Carp, *Myloparyngodon Piceus

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Abstract The study is carried out on the effect of drilling noise and vibration on growth of grass carp, *Myloparyngodon Piceus*, by using cut-fin marking method *in situ*. Compared with other methods, the method is more appropriate, for its operation is simpler and more data may be obtained under the same condition. The results show that drilling noise and vibration have significant effect on the growth of grass carp. Critical equivalent noise and vibration grade (*Nleq* and *Vleq*) are about 84.4 dB and 90.2 dB, and the affecting radius is about 8.5 m. The effect of drilling noise and vibration could be influenced by some factors, such as duration of pollution and body weight of grass carp, *etc.* Grass carp's growth could rapidly recover after removing drilling noise and vibration, indicating that the drilling noise and vibration do not damage the fish organs and the effect is reversible. Therefore, the effect mechanism may be due to the activating response of non-hearing system.

Keywords Drilling noise and vibration, Growth, Grass carp

Around the Bohai Sea, there exist 5 large oil fields, including Liaohe, Shengli, Dagang, Jidong, and Bohai oil fields. This area is also the most developed aquiculture region of north China. In recent years, a series of environmental problems caused by petroleum exploration and exploitation have become an obstacle to the co-development of aquiculture and petroleum industry. The noise and vibration pollution are considered to be one of the most serious environmental problems. Some studies have been published on the effect of drilling noise on human body^[1, 2, 3, 4, 5], but the effect of noise pollution on fish's growth in different conditions has been rarely reported so far.

Grass carp, *Myloparyngodon Piceus*, is the main cultured fish species in the region. This study is helpful to revealing the effect features caused by drilling noise and vibration. Cut-fin marking method applied in this study greatly simplifies the operation of simulating experiment *in situ* and more data may be obtained under the same condition.

1 Materials and methods

The experiment was carried out on the spot at No.15 exploration well of Jinzhou oil extraction factory, Liaohe oil field from May to June of 1999. The well is located in the largest reed field in China. In the area the terrain is level and open, the surface geological condition is uniform, and there

are no other sources of noise and vibration nearby.

1.1 Material resource and acclimation

Grass carp, *Myloparyngodon Piceus* has been obtained from the fish farm at Dawa County, Panjin, near the experiment spot. Firstly, grass carp is acclimatized after being treated with Florfenicol solution ($C = 4\text{ mg/L}$). Then, a cut-fin sign is marked at the dorsal fin of grass carp and then they are put into the experiment tanks (1 m^3) for further acclimation, when the feeding of the fish tends to be in normal. In order to prevent the marked part of dorsal fin from being infected, the water is treated with Florfenicol solution ($C = 1\text{ mg/L}$) for 3 days. The experiment starts after the feeding has become normal again.

1.2 Experiment settings in situ and methods

Simulating experiment method on the spot is adopted in this study. Fig. 1 shows the plane setting of the experiment area. $5\text{ m} \times 6\text{ m}$ canvas experiment canopies are constructed in the location of 5 m, 20 m, 40 m, 40 m, 60 m, 140 m, 220 m, $> 2\,000\text{ m}$ from the polluted source, respectively. In each

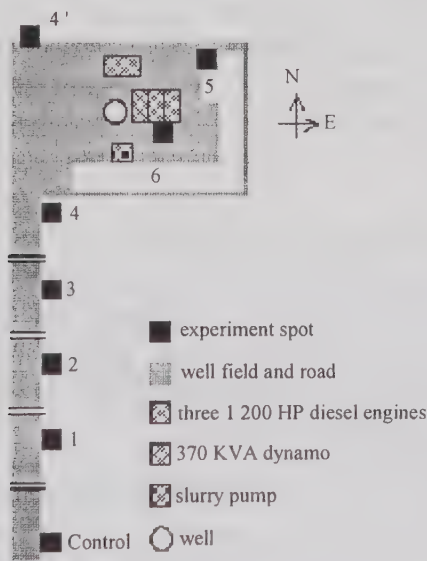


Fig.1 Experiment setup *in situ*

canopy, one 1 m^3 fiberglass reinforced plastic test tank is imbedded 40 cm under the ground and then tamped, and one 6 m^3 storage pond with aerating and water exchange settings is set up. Each test is conducted in duplicate. In each tank, there are 18 fish classified into three groups, each group including 6 fish with about (9.3 ± 2.6) g, (52.5 ± 9.0) g and (222.9 ± 26.0) g in body weight, respectively. All the test data are obtained from the group of (52.9 ± 9.0) g in body weight, except the weight experiment. The cut-fin marking method is to cut 2/3 of one thorn at dorsal fin of the fish. According to the situation of the thorn cut at dorsal fin, the test fish in each tank could be distinguished. The experiment of fish growth is run for 16 d. During the test period, the fish is weighed once every 8 d. Electronic balance is used to weigh the fish, with the precision being 0.1 g. In the

recovering growth experiment, grass carp of No.6 canopy significantly affected by drilling noise and vibration is transferred to the control so as to observe the growth recovering status of the test fish. In the test, the water is aerated and changed once in every 4 d, the renewal being 3/4 of the whole water volume. Tap water from Jizhou oil extraction factory is pumped into aeration tanks, and used for the test over 1 d. During the test, the dissolved oxygen content is over 6 mg/L and the water temperature (18.2 ± 1.8) °C. Fish diet is bought from market. Test fish are fed twice every day at 7:00 and 15:00. All data are determined under the maximal feeding level. During the test, the drilling noise and vibration in the 8 test stations are monitored for 24 h every 6 d. Monitored indexes mainly include the frequency features of drilling noise, drilling noise and vibration intensities, and their change regularity with time, *etc.* The determination instruments are noise frequency analysis meter (HS-6288 model) and environmental vibration analysis meter (AWA-6256 model).

1.3 Calculating method

In order to avoid the growth diversity caused by fish weight, specific growth rate (*SGR*) is used to express the growth rate of grass carp in the paper:

$$SGR = [(\ln W_t - \ln W_0) / t] \times 100 \%^{[6]}$$

Where W_t = grass carp's weight at the end of the experiment,
 W_0 = grass carp's weight at the start of the experiment,
 t = duration of the experiment.

2 Results

2.1 The pollution features of drilling noise and vibration

In this study, the noise and vibration field are even, approximately circular. The results of 24 h continuous monitor indicate that the drilling noise and vibration may basically be regarded as being continuous and stable. The distances of various experiment station from the pollution source and the equivalent noise grades and vibration grades are listed in Tab. 1. Based on the data in Tab.1, the

Tab. 1 Drilling noise and vibration intensities of different test stations and their changes with distance

No.	Distance (m)	Noise intensity (dB)			Vibration intensity (dB)		
		<i>NLeq</i> ± SD	<i>NL</i> _{max}	<i>NL</i> _{min}	<i>VLeq</i> ± SD	<i>VL</i> _{max}	<i>VL</i> _{min}
Control	>2000	57.9± 7.1	64.4	48.9	59.9± 4.6	70.3	51.4
1	240	60.8± 4.6	72.4	54.5	63.7± 6.2	75.0	55.0
2	160	65.1± 4.4	73.6	58.7	66.2± 4.4	75.9	56.5
3	80	68.7± 2.8	74.4	64.4	68.6± 7.6	85.7	57.7
4	40	71.1± 2.1	75.9	67.6	76.7± 6.1	88.3	64.7
4'	40	74.4± 2.6	79.1	69.6	76.0± 2.7	81.2	68.6
5	20	76.6± 2.5	80.2	70.1	83.6± 2.5	89.9	79.0
6	5	94.9± 1.7	97.4	91.4	101.7± 1.6	104.2	99.0

average attenuation coefficient of drilling noise and the average attenuation coefficient of drilling vibration could be obtained, viz $\alpha = 0.002$, and 0.019 , respectively. Then according to the formula of noise attenuation:

$$L = L_0 - 20 \lg (r / r_0) - \alpha (r - r_0),$$

Where L = sound pressure grade (dB) of each determined site,

L_0 = the known sound pressure grade (dB),

r = the distance (m) of each determined site from the sound source,

r_0 = the distance (m) of the known site from the sound source,

α = the attenuation coefficient,

the attenuation formulas of drilling noise and vibration could be obtained, viz:

$$N_{leq} = 94.91 - 20 \lg 0.2D - 0.002D, \text{ and}$$

$$V_{leq} = 101.80 - 20 \lg 0.2D - 0.019D, D \geq 5 \text{ m}$$

Figure 2 shows the frequency spectrum features of drilling noise. It can be seen that the frequency of drilling noise is mainly distributed in the low frequency section (under 2 KHzs). The spread of sound is closely related to its frequency. The higher is the sound frequency, the shorter is the sound wavelength and the more significant is the sound direction, and the faster is the sound disappearing speed as well. It may be also found from Figure 2 that the attenuation velocity of sound waves is relatively slow when the central frequency is lower than 2 KHzs, while the attenuation velocity of sound waves is fairly fast when the central frequency is higher than 2 KHzs. During the experiment, the frequency characteristics of drilling noise among the experiment sites do not show significant difference.

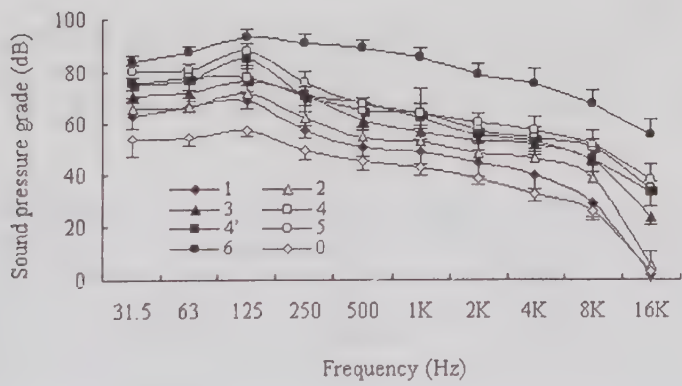


Fig. 2 Frequency spectrum feature of drilling noise pollution at different station

2.2 The effects of drilling noise and vibration on the specific growth rate

Table 2 shows the change tendencies of grass carp's specific growth rates with drilling noise and vibration intensity. Through variance analysis of all the test data, it could be seen that the grass carp's specific growth rates shows significant difference ($0.05 > P > 0.01$). By using t-test, it could be

found that drilling noise and vibration have significant effect on the grass carp's specific growth rate when the equivalent noise and vibration grade are up to 94.9 dB and 101.7 dB, the grass carp's specific growth rate constituting 39.7 % of that of the control.

Tab. 2 The effect of different noise and vibration intensities on specific growth rate

No.	Noise and vibration intensity (dB)		Num. of fish	SGR $\pm$ SD % W.W.	Variance analysis	t-test*(P value)
	NLeq $\pm$ SD	VLeq $\pm$ SD				
Control	57.9 $\pm$ 7.1	59.9 $\pm$ 4.6	12	0.78 $\pm$ 0.02		
1	60.8 $\pm$ 4.6	63.7 $\pm$ 6.2	12	0.94 $\pm$ 0.17		0.2609
2	65.1 $\pm$ 4.4	66.2 $\pm$ 4.4	12	0.73 $\pm$ 0.16	P= 0.0115	0.1571
3	68.7 $\pm$ 2.8	68.6 $\pm$ 7.6	12	1.03 $\pm$ 0.41	d.f. = 84	0.2823
4	71.1 $\pm$ 2.1	76.7 $\pm$ 6.1	12	0.81 $\pm$ 0.26		0.2930
5	76.6 $\pm$ 2.5	83.6 $\pm$ 2.5	12	0.87 $\pm$ 0.26		0.4332
6	94.9 $\pm$ 1.7	101.7 $\pm$ 1.6	12	0.31 $\pm$ 0.17		0.0023

2.3 The ecological factor effect of drilling noise and vibration on fish growth

2.3.1 The effect of pollution duration

It could be seen from Table 3, when the drilling noise and vibration last 8 d and 16 d respectively, the change tendencies of grass carp's specific growth rates with drilling noise and vibration intensity are basically similar. The results of variance analysis indicate that drilling noise and vibration have

Tab. 3 The effect of duration on the growth under different pollution level

No.	Duration 8d			Duration 16d		
	SGR $\pm$ SD % W.W.	Variance analysis	t-test* (P value)	SGR $\pm$ SD % W.W.	Variance analysis	t-test* (P value)
Control	0.80 $\pm$ 0.26			0.78 $\pm$ 0.02		
1	0.86 $\pm$ 0.30		0.2314	0.94 $\pm$ 0.17		0.2609
2	0.70 $\pm$ 0.25	P= 0.0033	0.1381	0.73 $\pm$ 0.16	P= 0.0115	0.1571
3	0.91 $\pm$ 0.40	d.f. = 84	0.3671	1.03 $\pm$ 0.41	d.f. = 84	0.2823
4	0.78 $\pm$ 0.38		0.3288	0.81 $\pm$ 0.26		0.2930
5	0.88 $\pm$ 0.20		0.1265	0.87 $\pm$ 0.26		0.4332
6	-0.04 $\pm$ 0.44		0.0031	0.31 $\pm$ 0.17		0.0023

significant influence on the grass carp's specific growth rate of the two groups, and the results of t-test further indicate that, only in No.6 being 5 m far from the pollution source ($N_{leq} = 94.9\text{dB}$, $V_{leq} = 101.7\text{ dB}$), the change of grass carp's specific growth rate is significant in comparison with that of the control. Moreover, it could be found that the influence of noise and vibration on the grass carp's specific growth rate of lasting 8 d is larger than that of lasting 16 d. If the test period is divided into two sections, in No.6 where the pollution influence is significant, the grass carp's specific growth rate of the former 8 d is negative, and that of the later 8 d does not show significant change in comparison with that of the control.

2.3.2 The effect of body weight

Grass carps of different body weights have different sensitivities to the drilling noise and vibration (Tab. 4). The results of variance analysis indicate that drilling noise and vibration have significant influence on fish growth in the weight range of the test, but the influence degree is different. Compared with the bigger individual grass carp of (222.9 ± 26.0) g in body weight, the influence degree of drilling of noise and vibration on the smaller individual of (9.3 ± 2.6) g in body weight is relatively low under the same experiment condition. The results of t-test show that, only in No.6, the nearest from the pollution source, the specific growth rates of the grass carp of different weights, compared with that of the control, show significant difference.

Tab. 4 The effect of body weight on pollution features

No.	(9.3 ± 2.6) g			(52.5 ± 9.0) g			(222.9 ± 26.0) g		
	SGR ±SD % W.W.	Variance analysis	t-test* (P value)	SGR ±SD % W.W.	Variance analysis	t-test* (P value)	SGR ±SD % W.W.	Variance analysis	t-test* (P value)
Control	1.63 ± 0.28			0.78 ± 0.02			0.35 ± 0.07		
1	1.59 ± 0.32		0.3827	0.94 ± 0.17		0.2609	0.37 ± 0.15		0.3872
2	—	P = 0.0382	—	0.73 ± 0.16	P = 0.0115	0.1571	0.41 ± 0.03	P = 0.0038	0.3526
3	1.65 ± 0.16	d.f. = 38	0.4120	1.03 ± 0.41	d.f. = 84	0.2823	0.50 ± 0.29	d.f. = 42	0.2913
4	1.41 ± 0.25		0.2893	0.81 ± 0.26		0.2930	0.37 ± 0.09		0.4146
5	1.41 ± 0.33		0.2468	0.87 ± 0.26		0.4332	0.38 ± 0.14		0.4014
6	0.80 ± 0.27		0.0310	0.31 ± 0.17		0.0023	0.14 ± 0.12		0.0008

2.4 The recovering growth of grass carp after being polluted by drilling noise and vibration

It can be seen from Table 5 that the growth of grass carp of No.6 significantly influenced by drilling noise and vibration recovers rapidly after being transferred into the control, and the specific growth rates during the recovering period, compared with that of the control, don't show any significant difference.

Tab. 5 Recovering growth after polluted by drilling noise and vibration

No.	Noise and vibration intensity (dB)		Num. of fish	SGR ±SD % W.W.	t-test*(P value)
	<i>NLeq</i> ± SD	<i>VLeq</i> ± SD			
Pollution group	94.9 ± 1.7	101.7± 1.6	12	0.31 ± 0.17	0.0034
Recovering group	57.9 ± 7.1	59.9 ± 4.6	12	0.88 ± 0.31	0.3128
Control group	57.9 ± 7.1	59.9 ± 4.6	12	0.78 ± 0.02	

3 Discussion

Because drilling noise and vibration pollution are produced by power equipment such as diesel engine, generator, slurry pump, *etc.* at the same time or alternatively, and it is very difficult to simulate the noise and vibration characteristics of drilling scene in the lab. In order to make the experiment result closer to the actual effect on aquaculture animals, such as grass carp, *etc.*, *in situ* simulating experiment method is chosen in this study. The following several problems have been considered in choosing the test scene: 1) There are no other pollution sources of noise and vibration around the test scene. 2) In order to make drilling noise and vibration transmit evenly, the test scene should be level and clear, the surface geological condition is evenly-distributed and is representative in the aquaculture area. 3) With the improvement of drilling technology in China, generally, it only takes 5 ~15 days to finish one ordinary producing oil well in the oil fields around Bohai Sea. In order to meet the time requirement of this study, two conditions must be ensured: one is choosing deep wells with 25 d drilling cycle, the other is that the preparing work of the experiment is done and finished with the construction of well site at the same time.

Because the *in situ* simulating experiment method is adopted and the noise and vibration always exist together in this study, the biological effect on grass carp is produced under the superposing function of noise and vibration. Under this test condition, the relationship between the distance from the pollution source and the noise equivalent sound grade or vibration equivalent grade could be respectively described as $1/(NLeq) = 0.0011 \ln(1/D) + 0.009$ or $1/(VLeq) = 0.0012 \ln(1/D) + 0.0086$. But it should be noted that the above-mentioned relationship between the distance from the pollution source and the equivalent noise grade or equivalent vibration grade had better be revised when used in other experiments according to the data actually determined, for the transmission of noise in air and vibration in ground would be respectively influenced by wind direction and geological condition to a great extent, even if it has been emphasized that the choice of test place and pollution characteristics should be representative.

The results of the study indicate that the influence of drilling noise and vibration on grass carp's growth is significant. By mathematical insert analysis between *P* values obtained from *t*-test and the equivalent noise grade or vibration grade and the distance from the pollution source, it could be obtained that the critical equivalent sound grade and critical equivalent vibration grade are 84.4 dB and 90.2 dB respectively and that the corresponding influencing radius is about 8.5 m, when *P* value

equals 0.05 and drilling noise and vibration begin to produce significant influence on grass carp's growth.

The effect of drilling noise and vibration on the growth of grass carp could be significantly influenced by some factors, such as pollution duration and fish's body weight. Within the time range of the test, the pollution effect of drilling noise and vibration on the fish growth at the initial stage is more significant than that in the subsequent stage, which may create the false impression that the pollution effect decreases with the extension of the pollution duration. The phenomena such as the excitation of sympathetic nerve, the contraction of blood vessels, the acceleration of the heart rhythm and respiratory rate and the disorder of stomach function would happen when the test fish are suddenly exposed to the polluted environment, where the noise and vibration are intense enough to cause their nervous response. The above could be expressed as the increase of metabolic energy and the decrease of consumption energy in energy budget. It could be found from the basic model of energy exchange in fish's body presented by Warren and Davis (1967)^[7] that the increase of metabolic energy and the decrease of consumption energy inevitably cause the decrease of growth energy. With the extension of pollution duration, the test fish are gradually adaptable to the polluted environment, possibly making the influence of drilling noise and vibration on fish weaker and weaker. But, it should be pointed out that the above-mentioned results might only be applied to a short-term pollution that has not caused irreversible organic damage to fish. Because only 5 to 15 days is needed to finish one ordinary producing oil well in the oil fields around the Bohai Sea, the results are sufficient to describe the effect of drilling noise and vibration on grass carp's growth quantitatively.

There are generally two kinds of effect of noise on human body: one is the temporary or permanent damage to the hearing organ which is usually irreversible, and the other is that, after the noise damage reaches the brain central nervous system through the sympathetic nerve, activating responses of some non-hearing systems are caused, such as contraction of the peripheral blood vessels, change of the heart rhythm, abnormality of the respiratory rate, disorder of gastrointestinal tract peristalsis and functional dysendocrinism, *etc.* The change of physiological function, only when human bodies are exposed to noise repeatedly for a long time, could be caused by the activating responses^[11, 8]. Under the test conditions, grass carp's growth could be significantly decreased due to the effect of drilling noise and vibration. However, grass carp could recover rapidly under normal conditions, indicating that the drilling noise and vibration do not damage the fish organs and the effect is reversible. Therefore, the effect mechanism may be due to the activating response of the non-hearing system.

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Induced Maturation and Spawning by Sex Pheromones in Female Mudskipper (*Boleophthalmus pectinirostris*)*

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Abstract Maturation of the 4th phase oocytes of mudskipper is induced in vitro by sex pheromones, the extract of ovary, testis and seminal vesicle, oxytocin and deoxycorticosterone (DOC). Maturation rates of oocytes are related to pheromones and their dosages. The single use of prostaglandin E_1 (PGE₁) is not effective in the induction of maturation, but the combination of PGE₁ with HCG promotes oocyte maturation rates. Maturation is induced by injections of the extract of the ovary at dosages of 0.01 cm³/a fish, seminal vesicle extract at dosages of 0.1 cm³/a fish, testis extract at dosage of 0.1 cm³/a fish, or PGE₁ at dosage of 10 μ g/fish, respectively. Among them, seminal vesicle extract is the most effective in the induction of maturation. The artificial nests, with the extract of the ovary, testis or seminal vesicle inside, attract more heterosexual mudskippers than homosexual mudskippers to enter. Especially, the extract of seminal vesicle is the most effective in attracting females. Female mudskippers could be induced to spawn by the extracts of ovary, testis and seminal vesicle placed inside both the ceramic and sponge nests. More spawned eggs and higher fertilization rates are observed in the ceramic nests than in the sponge ones.

Keywords *Boleophthalmus pectinirostris*, sex pheromones, maturation and spawning

1 Introduction

Mudskipper (*Boleophthalmus pectinirostris*) inhabits muddy burrow in the intertidal mudflats of the temperature zone, feeding mainly on benthic diatoms and adapting to a wide range of salinity^[1-3]. Although it is small in size, the mudskipper is delicious, nutritious and has a high market value. Fish farmers in Southeastern Mainland China are eager to culture this species. However, at present the natural resource of the fish has been decreasing or disappearing in some areas because of overfishing and destruction of the intertidal mudflats over the past two decades. As a result, natural fry can only meet the demands for the small area culture. A larger number of artificial fries have not been produced for farming by now^[4]. Liao (1972) began to study the larval cultural techniques of this species, but by 1980 only two fries had been obtained because of its special ecological habits and difficulties of larval rearing^[5]. In 1987 Zhang Qiyong *et al.* started to conduct the artificial propagation and breeding of the mudskipper, and made a breakthrough in the fry number, obtaining 7 000 fries in the same year^[6]. At present the mudskippers fertilized eggs are mainly obtained from artificial fertilization. Hence, it is difficult to obtain enough fry to meet the demands for farming^[4]. In order to obtain a larger number of

fries, it is important to induce natural maturation, mating and spawning of the broodfish. For this purpose, it is very necessary to study the reproduction physiology of the mudskipper.

Many scholars have studied the effects of the sex pheromones on fish reproduction for more than 10 years^[7-11]. Sex pheromones are the chemical substances secreted and released by animals, causing one or more specially physiological responses of other conspecific individuals. The sex pheromones of teleosts are almost sex hormones and their metabolites, which function not only as internal chemical signals to the body receptors, but also as external chemical signals in physiological behaviors for both the releaser itself and the other conspecific individuals when they are released to waters^[7]. Sex pheromones play an important role in fish reproductive behaviors, such as courtship, mating, and induction of spawning between females and males^[9, 12-14]. It is reported that sex pheromones are found in the ovarian fluid, semen and seminal vesicle fluid of mature fish. They are secreted and released by ovarian granulosa cells and interstitial cells of testes or seminal vesicle. It is indicated that mature fish release sex pheromones into water, which have an effect on the reproductive behaviors of heterosexual individuals. For example, the holding waters of ovulated goldfish (*Carassius auratus*), ovulated ayu (*Plecoglossus altivelis*) and female trout (*Oncorhynchus mykiss*) could strongly attract heterosexual individuals^[15-17].

So far, there have been no reports on the effects of sex pheromones on fish reproduction in China. The aim of the present study is to investigate the effects of sex pheromones of mature ovarian fluid, semen, seminal vesicle fluid and PGE₁ on oocyte maturation, on attracting the broodfish to enter the artificial nests and on mating and spawning in the mudskipper, in order to provide scientific data for inducing natural spawning of this species in fry production practice.

2 Materials and methods

2.1 Animals

The mudskippers are collected from Jiulong Jiang Estuary, Xiamen, Fujian, during the spawning season from April to May. The females with swollen abdomen and a red round genital papilla and the males with a peaked triangle genital papilla are selected for the experiments. Females are 77 ~ 140 mm in body length with an average of 105.2 mm, and 6.5 ~ 32.8 g in body weight with an average of 20.5 g. Males are 73 ~ 127 mm in body length with an average of 100.4 mm, and 6.5 ~ 20.5 g in body weight with an average of 16.5 g. The gonadal maturity of both females and males are at the IV-V stages.

2.2 Extract of ovary, testis and seminal vesicle

Ripe broodfish with gonadal maturity at the V stage are used to obtain the extracts. 1 mL of saline is added to 1 gram of ovary removed from the sacrificed broodfish. After being fully stirred up, the samples are centrifuged for 5 min at 3 500 r/min and then the ovarian extract (supernatant) is obtained. Because of their small sizes, four pairs of ripe testes (total weight 0.05 g ± 0.01g) or four pairs of ripe seminal vesicles (total weight 0.07 g ± 0.01g) are homogenized together. 1 mL of saline is added to the homogenate, which is centrifuged for 5 min at 3 500 r/min and then the testis extract or seminal vesicle extract (supernatants) is obtained.

2.3 Hormones

Prostaglandin E₁ (PGE₁) and deoxycorticosterone (DOC) are purchased from the U.S. Sigma Company, oxytocin from the Third Pharmaceutical Company of Harbin, and human chorionic gonadotropin (HCG) from Maanshan Biochemical Company of Anhui Province and Hormonal Company of Ningbo.

2.4 Methods

2.4.1 In vitro experiments

Oocytes are obtained by squeezing the female abdomen and examined. Females with ovaries at the stage IV are chosen for the experiment. The fishes are dissected and the ovaries are removed. Ovarian membrane torn and oocytes are separated carefully. About one hundred oocytes at the phase IV are chosen and cultured in a 200 mL petri dish filled with 100 mL of culture medium, which is prepared by sterilized seawater at salinity 10 containing 40 units of penicillin per mL.

Medium dosages are as follows: ovarian, testis and seminal vesicle extracts are 1×10^{-4} , 1×10^{-3} and 1×10^{-2} (V/V) respectively; PGE₁ and DOC are 0.1 μ g/mL and 1 μ g/mL, respectively; and oxytocini is 0.01 U/mL and 0.05 U/mL. All of the above extracts and hormones have a control group.

Water temperature is 25 °C ~ 26.5 °C during the experiments. After 24 h of cultivation, 60 oocytes are taken randomly from each experimental group, their maturity is examined under the microscope and the maturation rates are calculated.

2.4.2 In vivo experiments

In vivo experiments include injections of extracts or hormones and nest attraction and spawning. Female mudskippers at the 4th mature stage are used for the injection experiment. They are divided randomly into different groups, with 10 to 11 fish each. Individuals are injected intraperitoneally twice at a 24 h interval, with extracts of ovary, testis, seminal vesicle, PGE₁ or oxytocini at different dosages. Fish maturation are examined every 12 h or 24 h after injections. Three days after injection, all tested females are dissected and oocyte maturation rates are calculated for all groups. During the experiment water temperature varies from 23 °C to 27 °C, and salinity is 17.

Nest attraction is conducted in the pools (5 m²/each). Artificial ceramic and sponge nests are placed on the pool bottom. 2 mL of plastic tubes, which contain extracts of ovary, testis and seminal vesicle and PGE₁, are hanged on the inside surface of the top half of the nests. The opening of the tube is filled in a small piece of cotton so that the extracts or hormones could slowly seep into the inner water of nests. The ripe broodfish are selected for experiments. They are introduced to the pools at a sex ratio of 1:1 and allowed to choose their favorable nests, to mate and to spawn. The number of females or males and spawning inside the nests are examined at 24 h and 48 h after the broodfish are introduced to the pools. Water temperature range from 26 °C to 28 °C. Salinity is between 28 and 31. The depth of water is maintained at 15 ~ 20 cm. The pools are covered with black cloth to keep a weak light environment.

3 Results

3.1 In vitro experiments

Maturation of oocytes is evaluated by the appearance of sphericity, transparence, bright and centralized lipid droplets and developed filaments. It is indicated in the Table 1 that extract of ovary, testis, and seminal vesicle at a dosage of 1 % (V/V) are not significantly effective in increasing the maturation rates of oocytes, neither are the three extracts effective in the induction of oocyte maturation at other dosages. The single use of PGE₁ is not effective in the induction of maturation, but the combination of PGE₁ with HCG significantly increases maturation rates of oocytes. Oxytocini and DOC are effective in inducing oocyte maturation.

Tab.1 In vitro oocyte maturation induced by pheromones in female mudskipper

Extract or hormone	Ovarian extract	Testis extract	Seminal vesicle extract	PGE ₁	PGE ₁ + HCG	Oxytocini	DOC	Control
	0.01 cm ³	0.01 cm ³	0.01 cm ³	10 μ g	10 μ g +100IU	1 Unit	10 μ g	0
Dosage /100cm ³	0.1 cm ³	0.1 cm ³	0.1 cm ³	100 μ g	100 μ g +100IU	5 Units	100 μ g	
	1 cm ³	1 cm ³	1 cm ³					
No. of mature oocytes / No. of examined oocytes	4/60	5/60	2/60	3/60	8/60	8/60	13/60	3/60
	11/60	4/60	3/60	5/60	36/60	14/60	15/60	
	2/60	9/60	10/60					
	6.7	8.3	3.3	5.0	20.0	13.3	21.7	5.0
Maturation rates (%)	18.3	6.7	5.0	8.3	60.0	23.3	25.0	
	3.3	15.0	16.7					

3.2 In vivo injection experiments

Female mudskippers are injected with sex pheromones at two different dosages and the results are shown in Table 2. After 24 h of injection, all tested fishes are responsive to sex pheromones. The effects of extract and pheromone on gonadal maturation are related to their dosages. Ovarian extract and seminal vesicle extract at two dosages and testis extract at higher dosage as well as PGE₁ are effective in the induction of gonadal maturation, with the most significant effect observed in the seminal vesicle extract. No mature fishes at lower dosages of testis extract and PGE₁ have been found (Tab. 2).

Tab. 2 Gonadal maturation induced by pheromone injection in female mudskipper

Extract & hormone	Dosage / fish	No.of fish	Maturation rates (%)		
			24 h	48 h	72 h
Ovarian extract	0.01 cm ³	10	10.0	30.0	40.0
	0.1 cm ³	11	18.2	36.4	45.5
Testis extract	0.01cm ³	10	0	0	0
	0.1cm ³	11	27.3	45.5	45.5
Seminal vesicle extract	0.01cm ³	10	20.0	40.0	50.0
	0.1cm ³	11	18.2	54.5	54.5
PGE ₁	1 μ g	10	0	0	0
	10 μ g	10	10.0	30.0	30.0
Control	0	10	0	0	0

3.3 Artificial nest experiments

3.3.1 The attractive effects of sex pheromones on broodfish

The results show that the number of broodfish observed inside both ceramic and sponge nests, where the extract of ovary, testes and seminal vesicle is placed, is obviously more than that of the control group. However, the total number of broodfish inside both ceramic and sponge nests, where PGE₁ is placed, is not obviously different from the control. Ovarian extract attracts more males than females to enter the nests, while testis extract and seminal vesicle extract attract more females than males to enter the nests, especially the seminal vesicle extract (Tab. 3).

Tab. 3 Attractive effects of pheromones on mudskipper entering the artificial nests

Times of experiment		ceramic nests (two nests for each pheromone)					Sponge nests (two nests for each pheromone)				
		Ovarian extract	Testis extract	Seminal vesicle extract	PGE ₁	Control	Ovarian extract	Testis extract	Seminal vesicle extract	PGE ₁	Control
First time	Total fish inside nests	5	5	6	3	3	6	6	6	3	3
	Female/male	2♀3♂	3♀2♂	4♀2♂	1♀2♂	2♀1♂	3♀3♂	3♀3♂	4♀2♂	2♀1♂	1♀2♂
	% of female and male	40 60	60 40	67 33	33 67	33 67	50 50	50 50	67 33	67 33	33 67
Second time	Total fish inside nests	5	4	4	3	3	5	6	10	2	3
	Female/male	2♀3♂	2♀2♂	3♀1♂	2♀1♂	1♀2♂	2♀3♂	4♀2♂	7♀3♂	1♀1♂	2♀1♂
	% of female and male	40 60	50 50	75 25	67 33	33 67	40 60	67 33	70 30	50 50	67 33
Third time	Total fish inside nests	6	5	9	4	3	10	8	6	3	3
	Female/male	2♀4♂	3♀2♂	7♀2♂	2♀2♂	1♀2♂	4♀6♂	5♀3♂	4♀2♂	1♀2♂	2♀1♂
	% of female and male	33 67	60 40	78 22	50 50	33 67	40 60	63 37	67 33	33 67	67 33
Total	Total fish inside nests	16	14	19	10	9	21	20	22	8	9
	Female/male	6♀10♂	8♀6♂	14♀5♂	5♀5♂	4♀5♂	9♀12♂	12♀8♂	15♀7♂	4♀4♂	5♀4♂
	% of female and male	37.5 62.5	57 43	74 26	50 50	44 56	43 57	60 40	68 32	50 50	56 44

3.3.2 Effects of sex pheromones on spawning

The results show that broodfish could spawn inside both the ceramic and sponge nests, where the extract of the ovary, testis or seminal vesicle is placed, but the spawning frequencies, the number of spawned eggs and the fertilization rates of mature eggs are related to the types of the nests. Broodfish

spawn more times inside the sponge nests than inside the ceramic nests, but both the number of spawned eggs and the fertilization rates inside the ceramic nests are significantly higher than those inside the sponge nests. PGE1 has no effect on inducing spawning of mudskippers. One spawning is recorded in the control group (Tab. 4).

Tab. 4 Effects of sex pheromones on spawning in mudskipper

Times of experiment		ceramic nest					sponge nest				
		Ovarian extract	Testis extract	Seminal vesicle extract	PGE ₁	Control	Ovarian extract	Testis extract	Seminal vesicle extract	PGE ₁	Control
First time	Spawned eggs	0	0	550	0	0	220	150	180	0	80
	Fertilization rates (%)	-	-	80	-	-	15	10	12	-	10
Second time	Spawned eggs	850	1 050	0	0	0	160	0	90	0	0
	Fertilization rates (%)	85	80	-	-	-	11	-	16	-	-
Total	Spawning times	1	1	1	0	0	2	1	2	0	1
	Total spawned eggs	850	1 050	550	0	0	380	150	270	0	80
	Mean fertilization rates (%)	85	80	80	-	-	13	10	14	-	10

Discussions

The extract of ovary, testis and seminal vesicle can induce oocytes to develop from the 4th phase to the 5th phase in vitro, and the extract of seminal vesicle is the most effective. However, most of oocytes die and the maturation rate is very low in the ovarian extract group at the highest dosage of 1×10^{-2} (V/V), because the culture medium turns turbid after 24 h of cultivation. Female muskipper with gonadal development at the 4th phase can not mature indoor, but some of them begin to mature after 24 h intraperitoneal injection with the extract of ovary, testis or seminal vesicle, and after 72 h of injection the maturation rate can reach 54.5 %. The extract of ovary, testis and seminal vesicle can attract broodfishes to enter the artificial nests. However, the ovarian extract attracts more males than females, while the testis and seminal vesicle extract attracts more males than females, especially the seminal vesicle being more effective. The experimental results in vitro and in vivo indicate that there exist sex pheromones in the extract of ovary, testis and seminal vesicle in muskipper, which can induce oocytes to mature, promote broodfish spawning and attract heterosexual individuals. Many broodfish spawnings are observed inside the ceramic and sponge nests, where the extract of ovary, testis and seminal vesicle is placed, while only one spawning is found in the control group, indicating that the sex pheromone can promote mudskipper spawning.

Female goldfish^[15], ayu^[16] and guppy (*Poecilia reticulata*)^[18] are able to attract conspecific males

and enhance the males ability of chasing females, probably because the mature female ovary can secrete one kind of sex pheromone this secretion is probably based on the presence of the mature oocytes^[15]. It is proven that this sex pheromone should be 4-pregnen-17 α , 20 β -diol-3-one (17 α , 20 β -P)^[19]. The effective mechanism of 17 α , 20 β -P is that it stimulates the male olfactory epithelium receptor and the stimulation is transmitted to pituitary-hypothalamus system through olfactory tracts, which causes the increase of the body levels of GtH or 17 α , 20 β -P. As a result, both milt quantity and number of spermatozoa in male increase and the behaviors of males chasing the females are strengthened. There exists one kind of sex pheromone in the seminal vesicle of African catfish (*Claria gariepinus*), which can attract conspecific females^[20-23]. It is indicated that this kind of sex pheromone is a steroid glucuronides mixture^[20], consisting of eight substances^[22]. Among them 5 β -pregnane-3 α and 17 α -diol-20-one-3 α glucuronide are the most effective, and their effects increase with the increase of dosages^[13, 22]. When immature female zebrafish (*Brachydanio reio*) are reared alone, they can not mature. But when they are put in mature male holding water or water containing the extract of testis, they could mature^[24]. There exist sex pheromones in the milt of mature male herring (*Clupea harengus pallasi*), which could greatly stimulate female and male reproductive behaviors^[25]. The mudskippers sex pheromones are obviously effective in attracting heterosexual individuals and promoting productive behaviors, but further study will be carried out to determine the levels of these sex pheromones.

Fish prostaglandins (PGs) have been identified in testis, ovary and blood^[26]. PGs could stimulate oocyte maturation of some teleosts^[27, 28]. The single use of PGE₁ is not directly effective in the induction of maturation of mudskipper oocyte in vitro, but the combination of PGE₁ with HCG becomes more effective. This result consists with the hypothesis that the mechanism of PGs for promoting oocyte maturation is to stimulate GTH release through the pituitary-hypothalamus system^[29]. Liu *et al.* (1992) found that PGE₂ levels of silver carps (*Hypophthalmichthys molitrix*) decreases significantly^[30], but PGF_{2 α} levels almost do not vary during spawning. The combination of PGE₂ with luteinizing hormone releasing hormone analogue (LHRH-A) could promote the maturation effects for carps^[31]. PGE₁ is not effective either in attracting broodfish or in inducing spawnig in the present experiment, indicating that PGE₁ may not be the sex pheromone affecting spawning in mudskippers. DOC is effective in inducing oocyte maturation in mudskippers, which consists with the stripped mullet (*Mugil cephalus*)^[32]. Oxytocini, a common spawning inducer for mammal, can promote PGs synthesizing and releasing, but its mechanism for inducing oocyte maturation in mudskipper needs to be studied.

Mudskippers have a certain choice of different types of nests. Different textural nests have different abilities to attract mudskippers. The texture of sponge nests is soft, while the texture of ceramic nest is solid. So the mudskipper prefers the former. This is probably related to the habits of this species, as it lives in intertidal soft mudflats in open sea. However, the fertilization rate of sponge nests is lower, because the sponge nest has small holes, in which spawned eggs are often embedded and the egg membrane breaks easily. On the contrary, the fertilization rate of ceramic nests is higher, because the inner surface of the ceramic nests is rough, which is favorable to the adhesion and fertilization of oocytes.

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